Measurement of Inclusive Charm Production in Two-Photon Collisions at LEP

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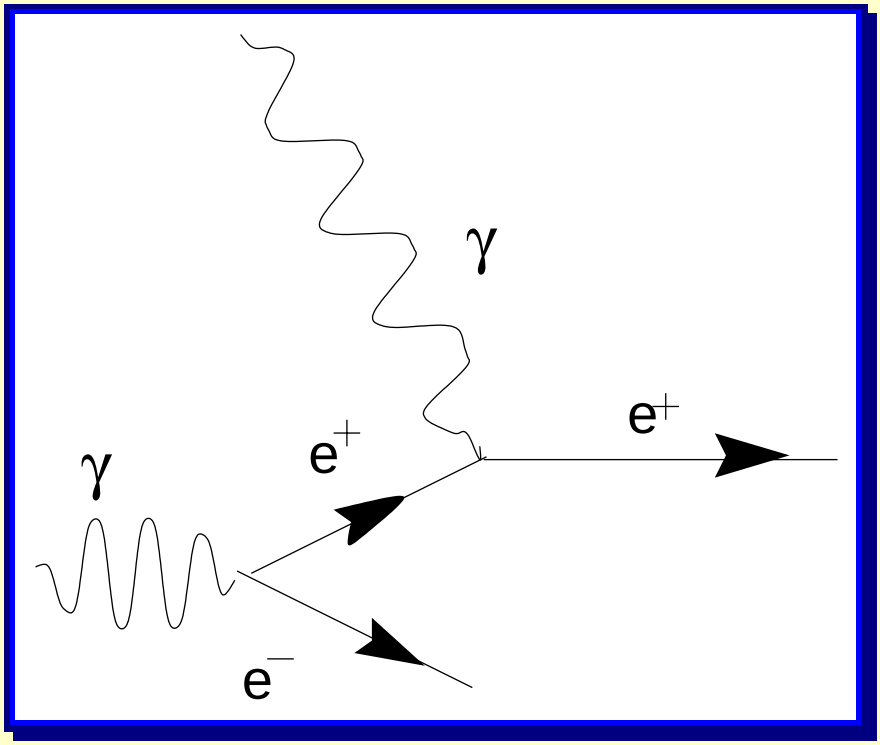
- Two-Photon Introduction
- L3 Detector
- Analysis & Results
- Summary & Outlook

Two-Photon Interactions

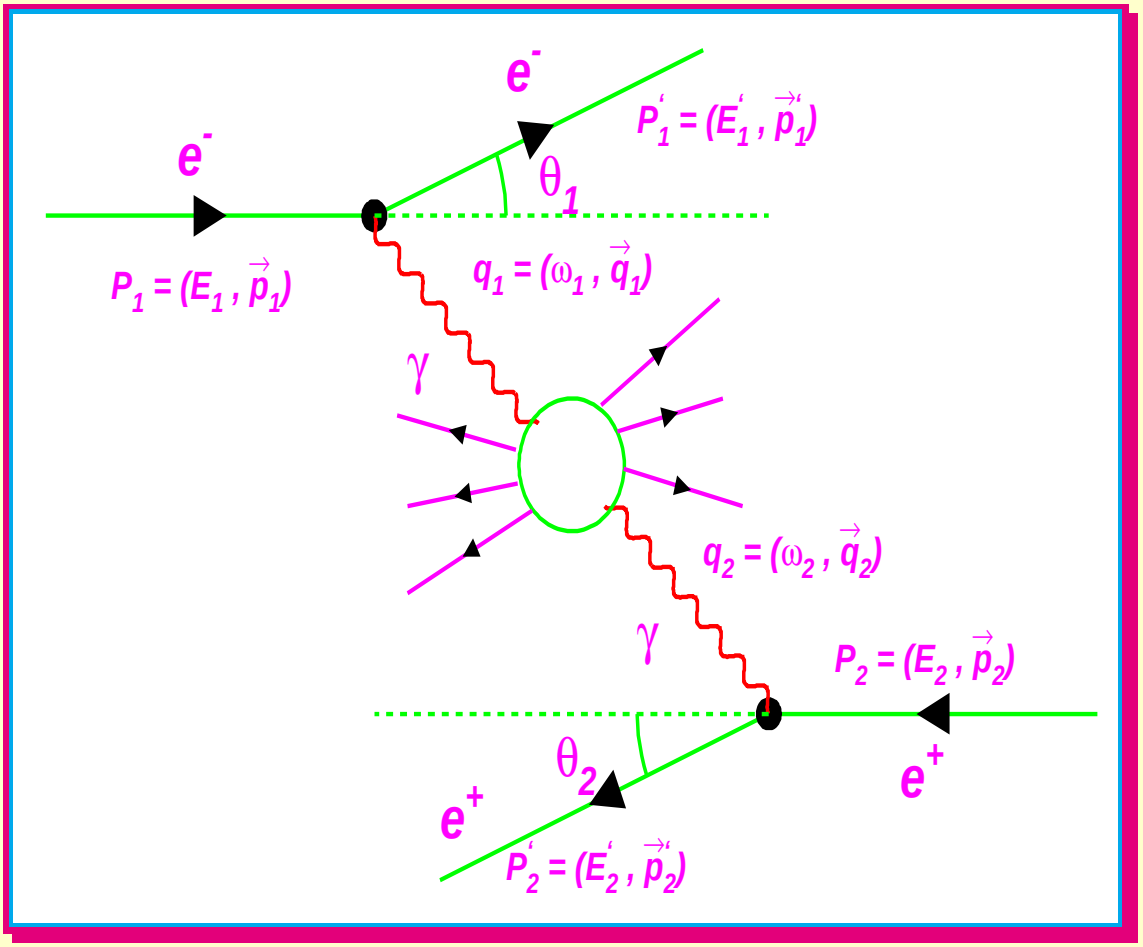


$$\Delta t \approx 1/\Delta E$$

The reaction, $\gamma\gamma \to X$, produces three different types of two-photon final states:

1. $\gamma\gamma \to \ell^+\ell^- \quad (\ell = e, \mu, \tau)$
2. $\gamma\gamma \to \rho, \phi, \omega, J/\psi$ **Vector Meson Dominance**
   VMD: main source of $\gamma\gamma \to hadrons$
3. $\gamma\gamma \to q\bar{q}$ & $\gamma g \to q\bar{q}$ **Direct, Resolved**
   main source of $\gamma\gamma \to Q\bar{Q}$ $(Q = charm, beauty)$

Two-Photon Interactions



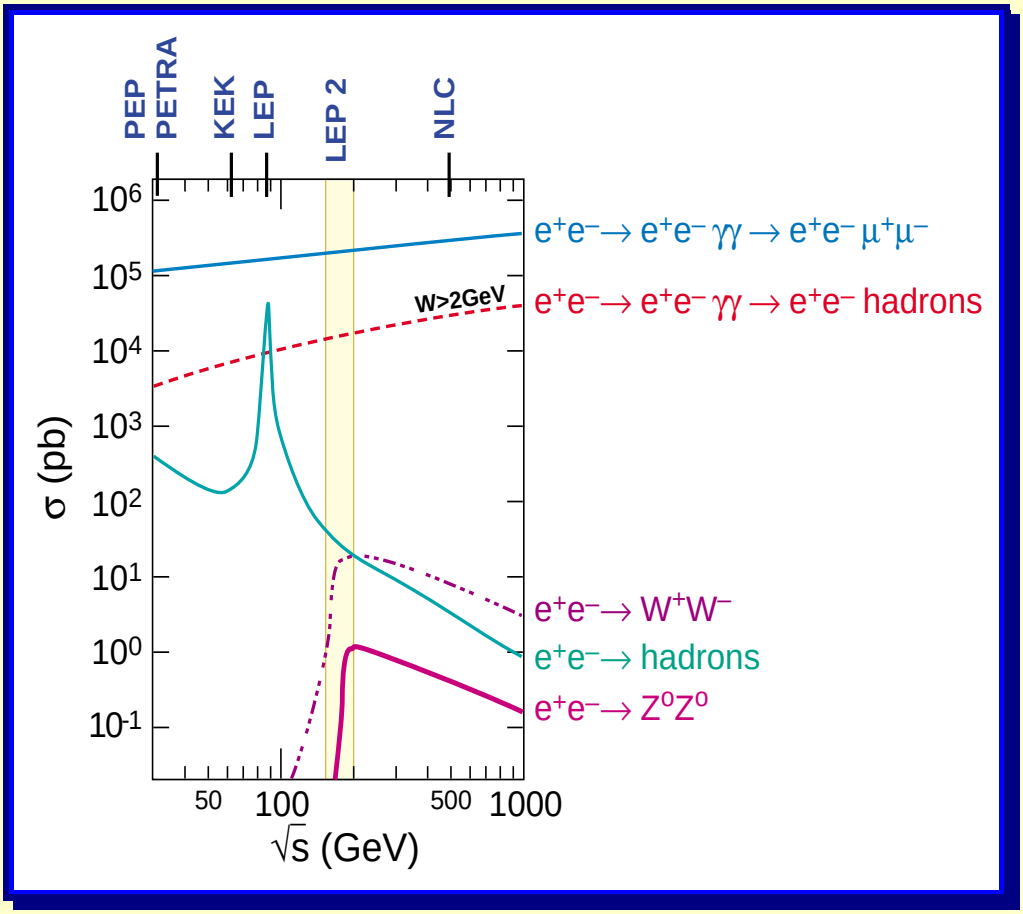
- $\mathbf{W^2_{\gamma\gamma} = (\sum_h E_h)^2 - (\sum_h \vec{p})^2}$

  Invariant mass is typically small in a e^+e^- collision compared to center-of-mass energy $\sqrt{s}$

- $\mathbf{Q^2_i = -q^2_i = 2E_iE'_i(1 - \cos\,\theta_i)}$

  Anti-tag condition ($Q_i^2 \approx 0$) real photons have a small transverse momentum, or virtuality

Two-Photon Interactions

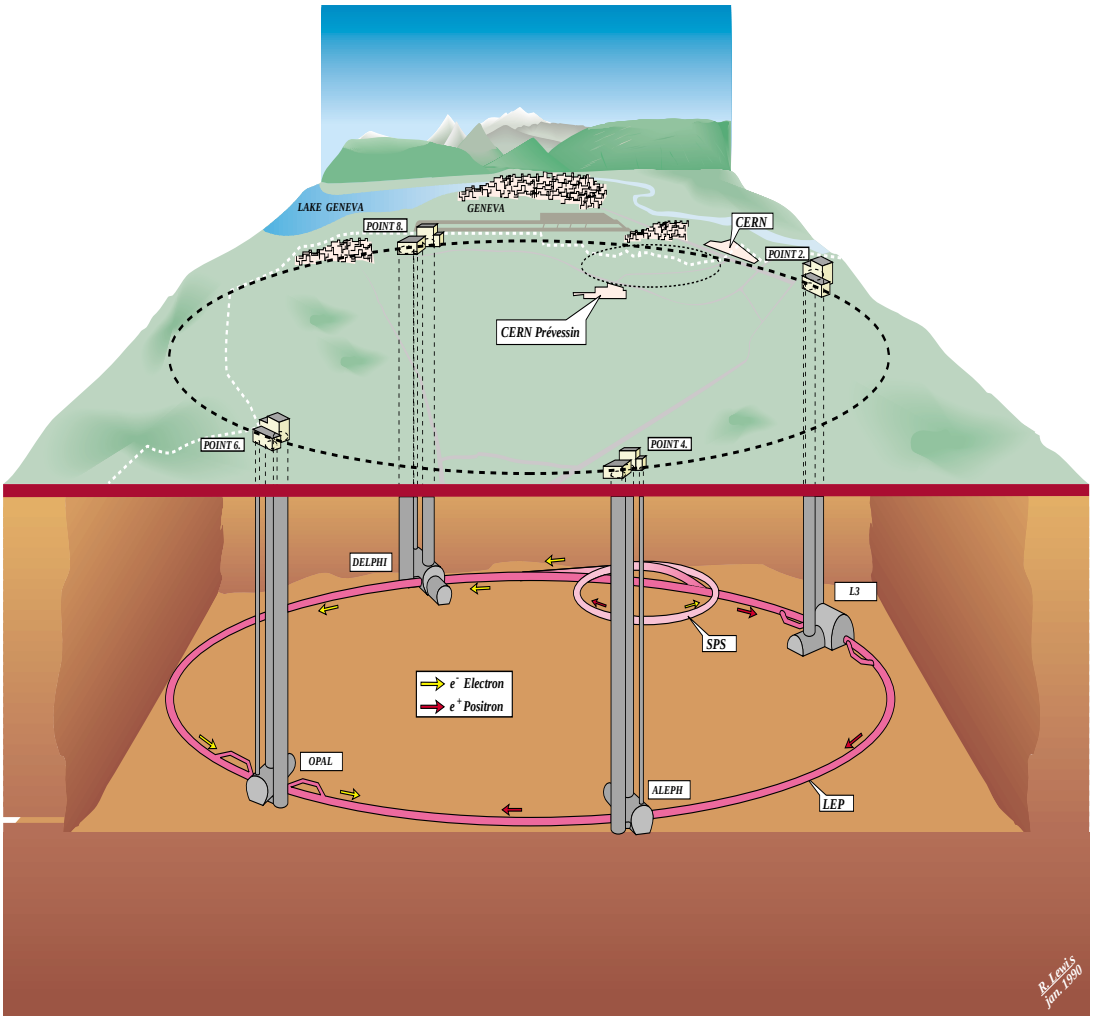


- **Annihilation Processes:**
  $\sigma(e^+e^- \rightarrow X) \propto 1/s$
  ...except resonance production such as Z^0

- **Two-Photon Processes:**
  $\sigma(e^+e^- \rightarrow e^+e^- X) \propto (ln(s/m^2_{elec}))^2$

- **Background to other processes.**

LEP Collider

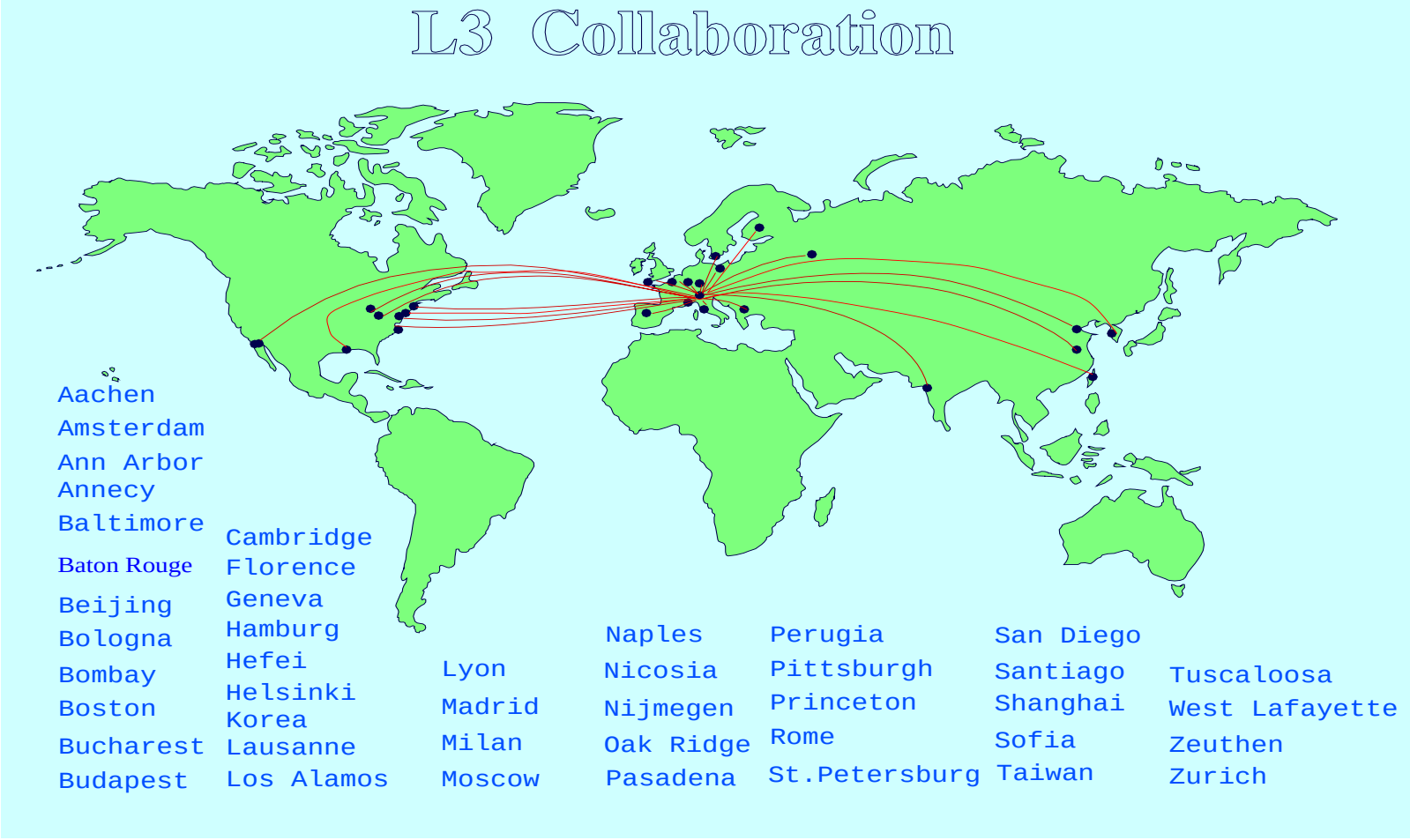


ALEPH, DELPHI, L3, OPAL

- **LEP1: 1989 - 1995** $\rightarrow \sqrt{s} \simeq 91$ GeV
- **LEP1: 1996 - 2000** $\rightarrow \sqrt{s} = 130 \sim 200$ GeV

EVENT $\equiv e^+e^-$ **interaction recorded to tape**

L3 Collaboration



LSU Members: Prof. Roger McNeil, Dr. Valeri Andreev, Alan L. Stone and Sepehr Saremi

Luminosity Measurement

The number of events for a physical process:

$$\mathbf{N_{events}} = \epsilon \cdot \sigma \cdot \mathcal{L}$$

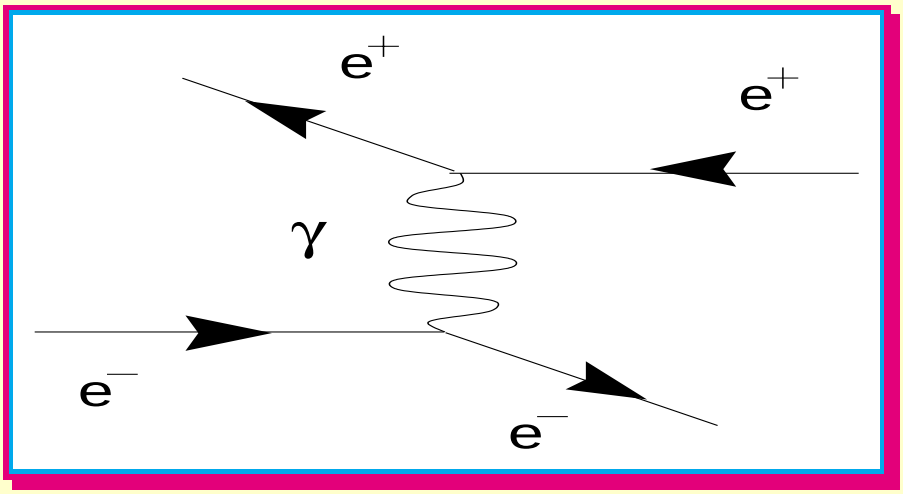
- ϵ = efficiency for detecting process
- σ = cross section (units of area: pb, nb, cm^2)
- $\mathcal{L}$ = integrated luminosity

$\mathcal{L}$ depends on Accelerator and Detector live time

Determine $\mathcal{L}$ using process known very well both theoretically and experimentally

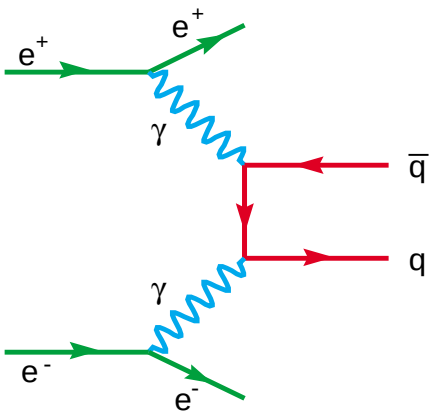
Bhahba Scattering: $\mathbf{e^+e^- \rightarrow e^+e^-}$

...very high rate for low angles

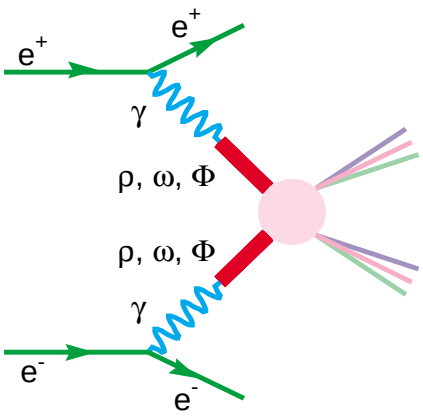


$$\mathcal{L}_{\mathbf{e^+e^-}} = \frac{\mathbf{N_{e^+e^- \rightarrow e^+e^-}}}{\epsilon\ \sigma_{\mathbf{e^+e^- \rightarrow e^+e^-}}}$$

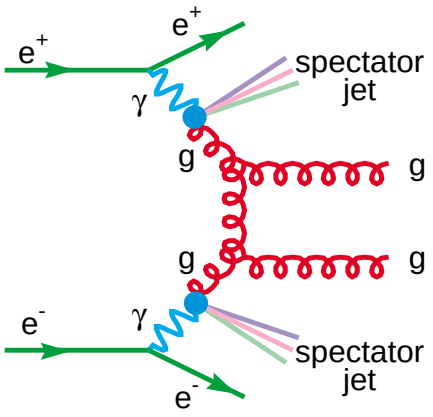
$\gamma\gamma$ Hadronic Production



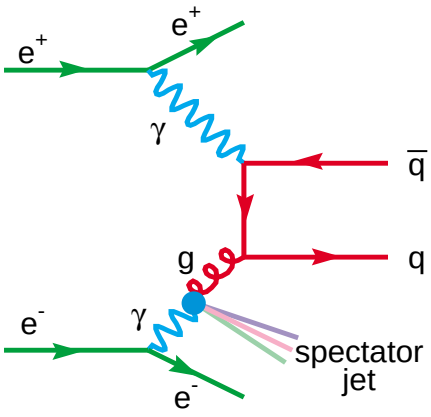
Direct



VDM



Double Resolved

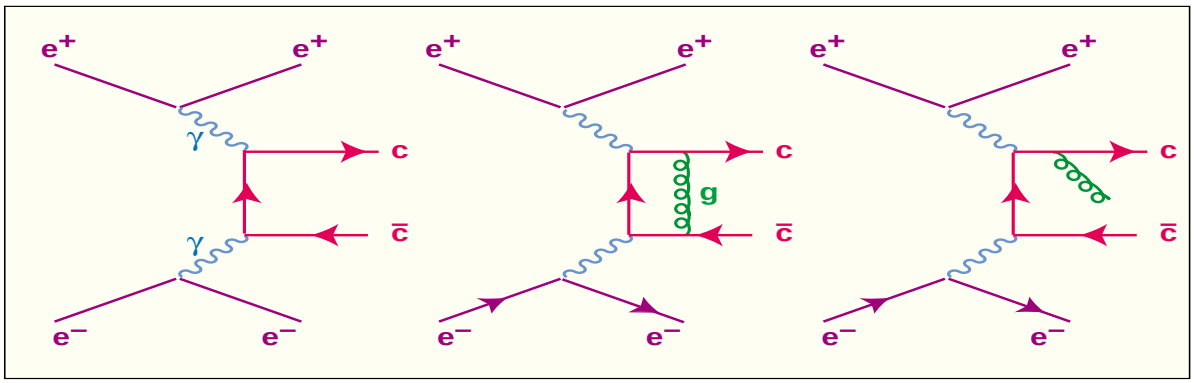


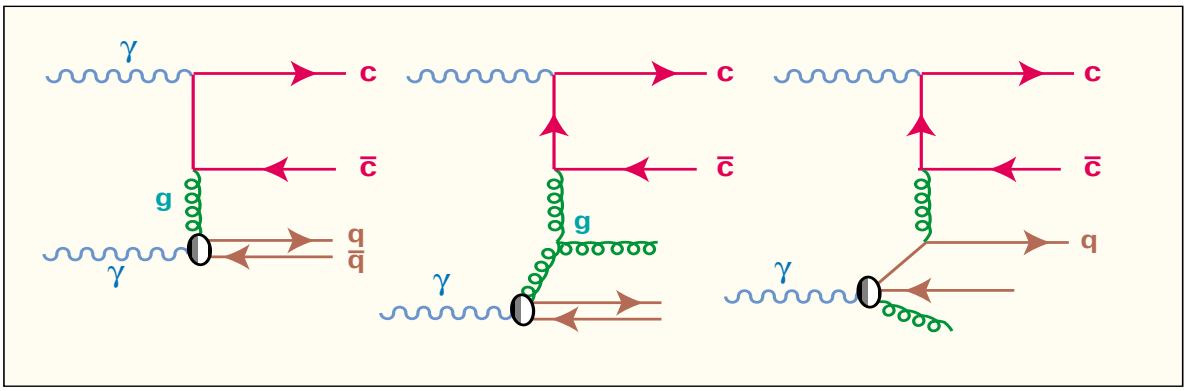
Single Resolved

- **Direct and Single Resolved Processes dominate in $e^+e^- \to e^+e^- c\bar{c}$ production**

Charm Production

Beauty production suppressed relative to charm due of smaller charge and larger mass



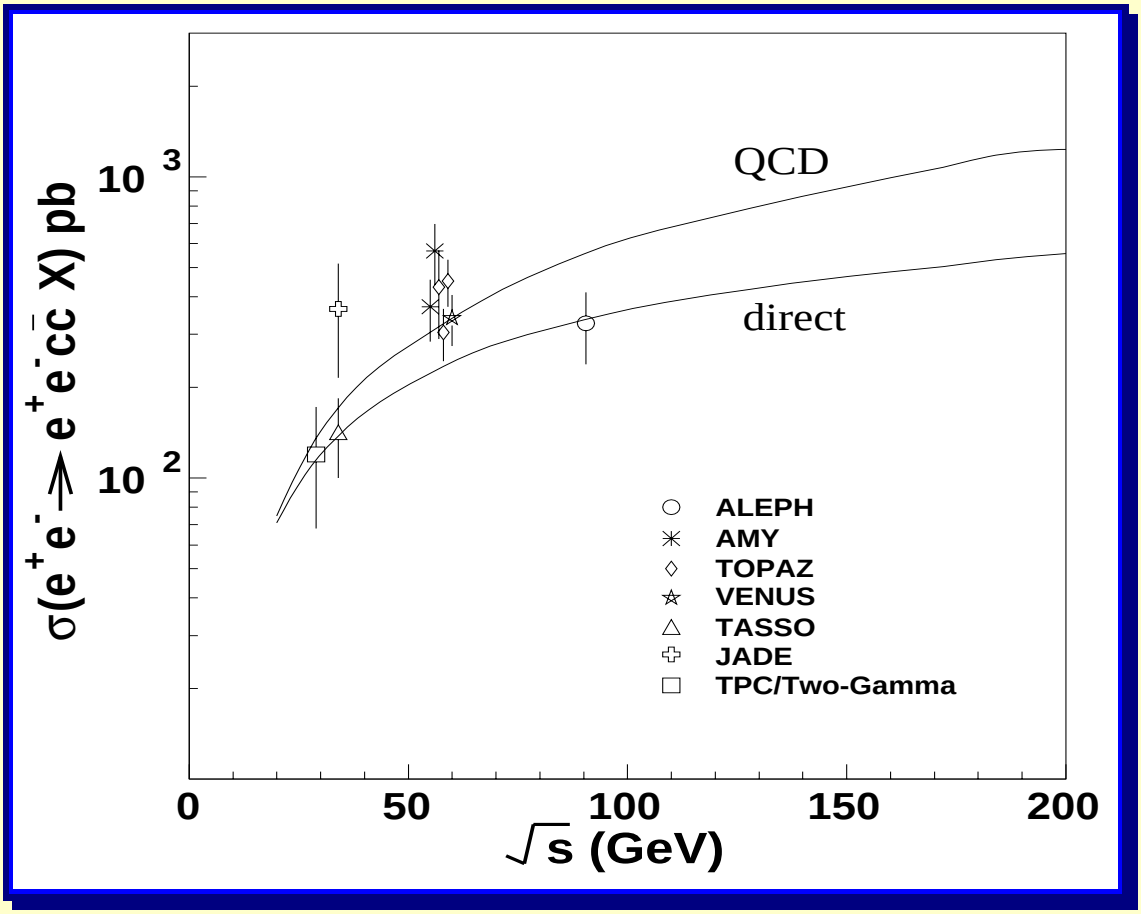


- **Direct: Born term + virtual and real QCD corrections**
  constrain mass of charm quark
- **Single resolved: $\gamma g \to c\bar{c}$**
  measurement of the gluon content in photon

At LEP2 energies, charm production from resolved processes expected to be comparable to direct

Theoretical Cross Section

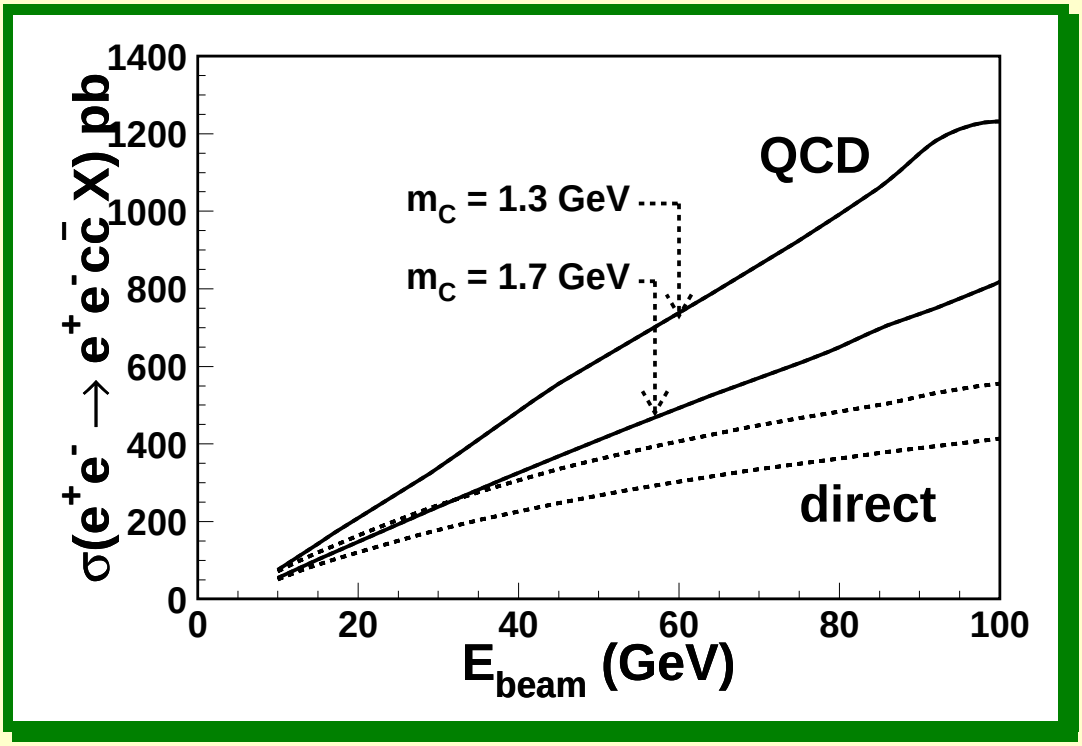
Next-to-Leading (NLO) Calculations

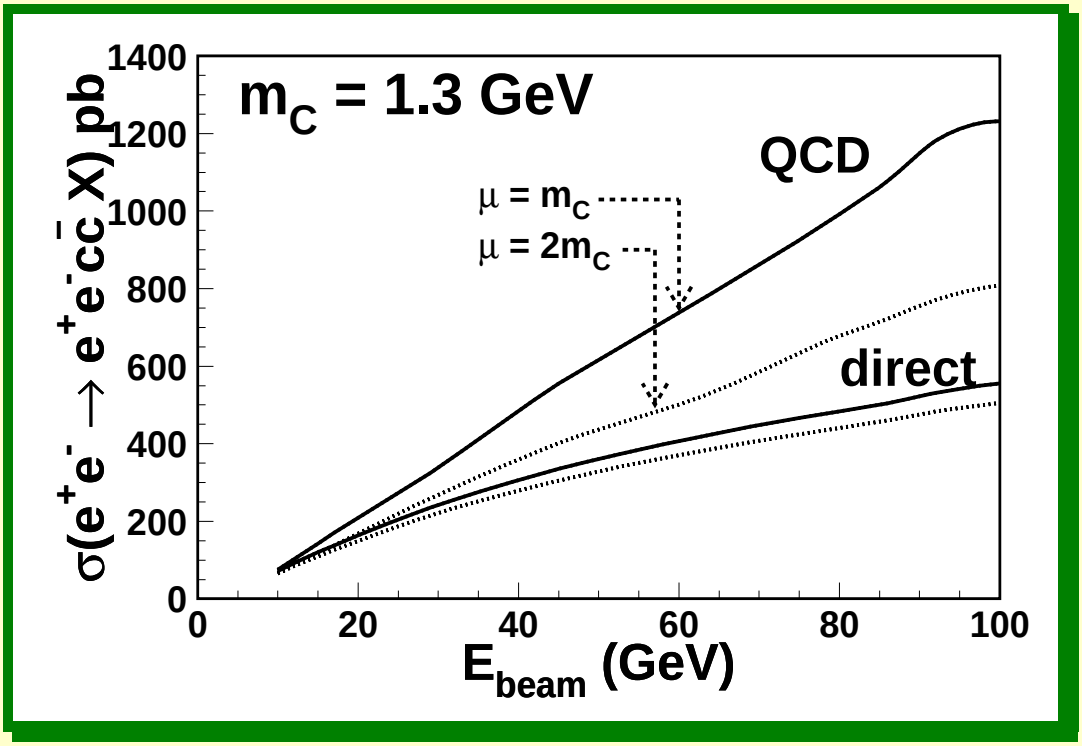


Ref: M.Drees, M.Kramer, J.Zunft & P.M. Zerwas
Physics Letters B 306 (1993) 371

- D^* tagging: $D^{*\pm} \to D^0\pi^\pm$
  (TPC/2γ, TASSO, JADE, TOPAZ, AMY, ALEPH)
- Semileptonic decays: $c \to s\ W^*$
  $\hookrightarrow \ell + \nu$
  (TOPAZ,AMY,VENUS)

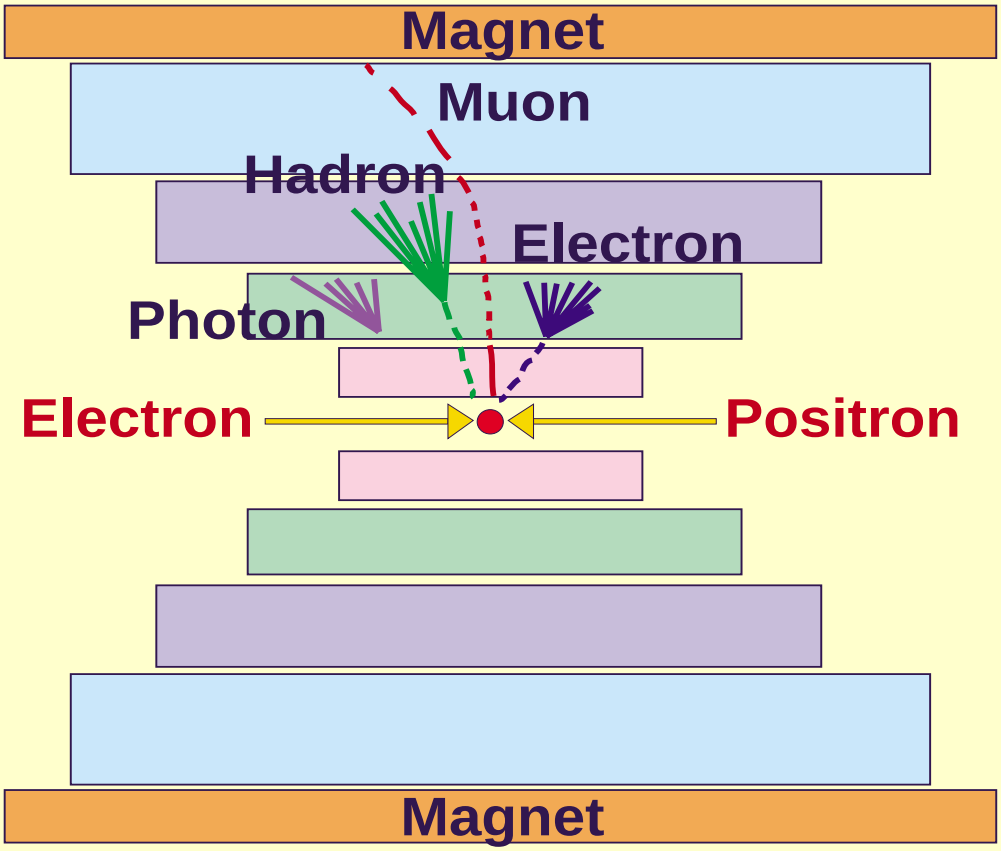
Charm Quark Mass





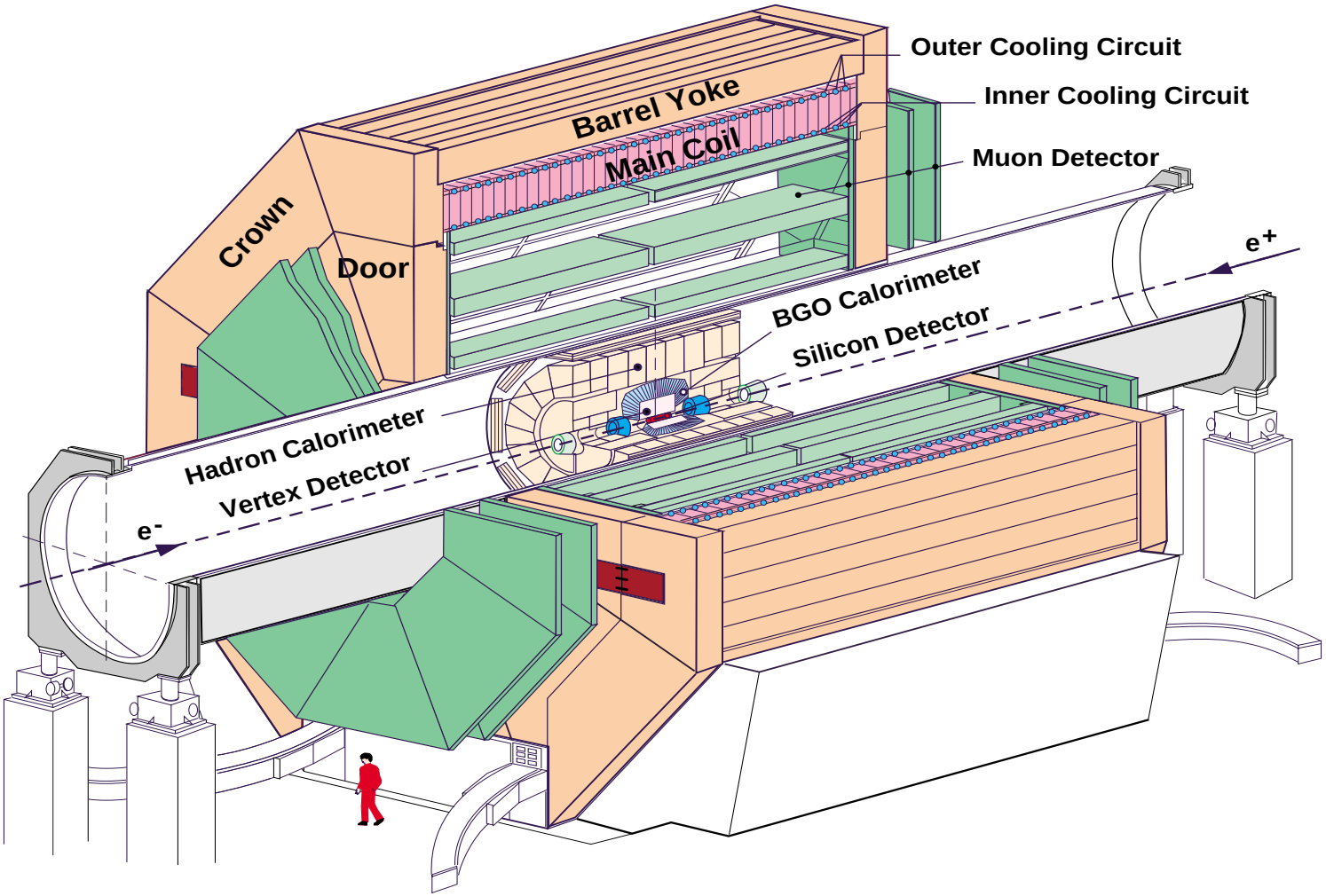
e^+e^- Collider Detector

Method of Particle Identification in the Detector



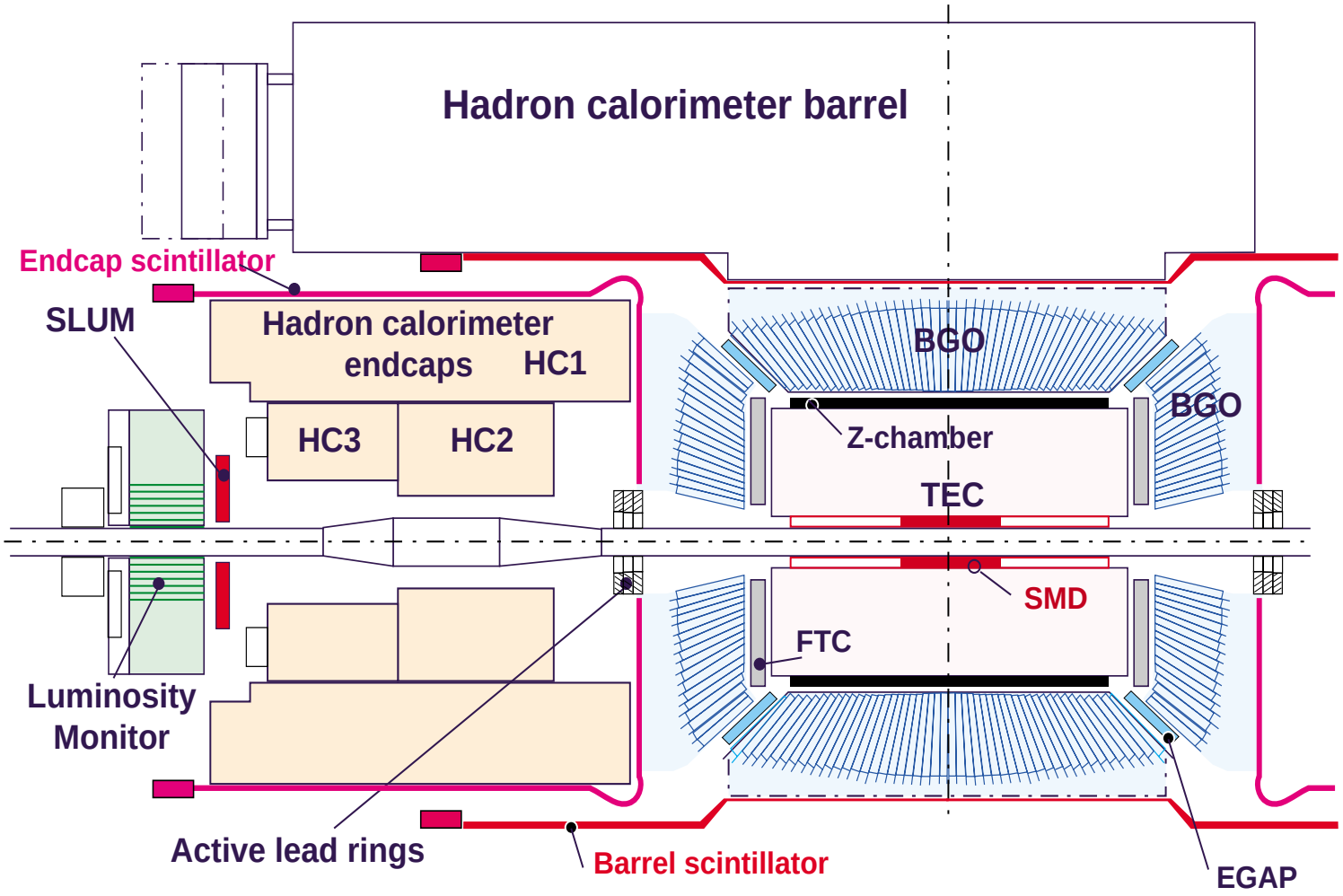
- Momentum of Charge Particles measured by curvature in magnetic field in Tracking Chamber
- Electrons & Photons measured in Electromagnetic Calorimeter
- Pions, Kaons, Protons measured in Hadron Calorimeter
- Muons penetrate Calorimeters to reach Muon Chambers

The L3 Detector



Excellent resolution for e, μ, γ measurements

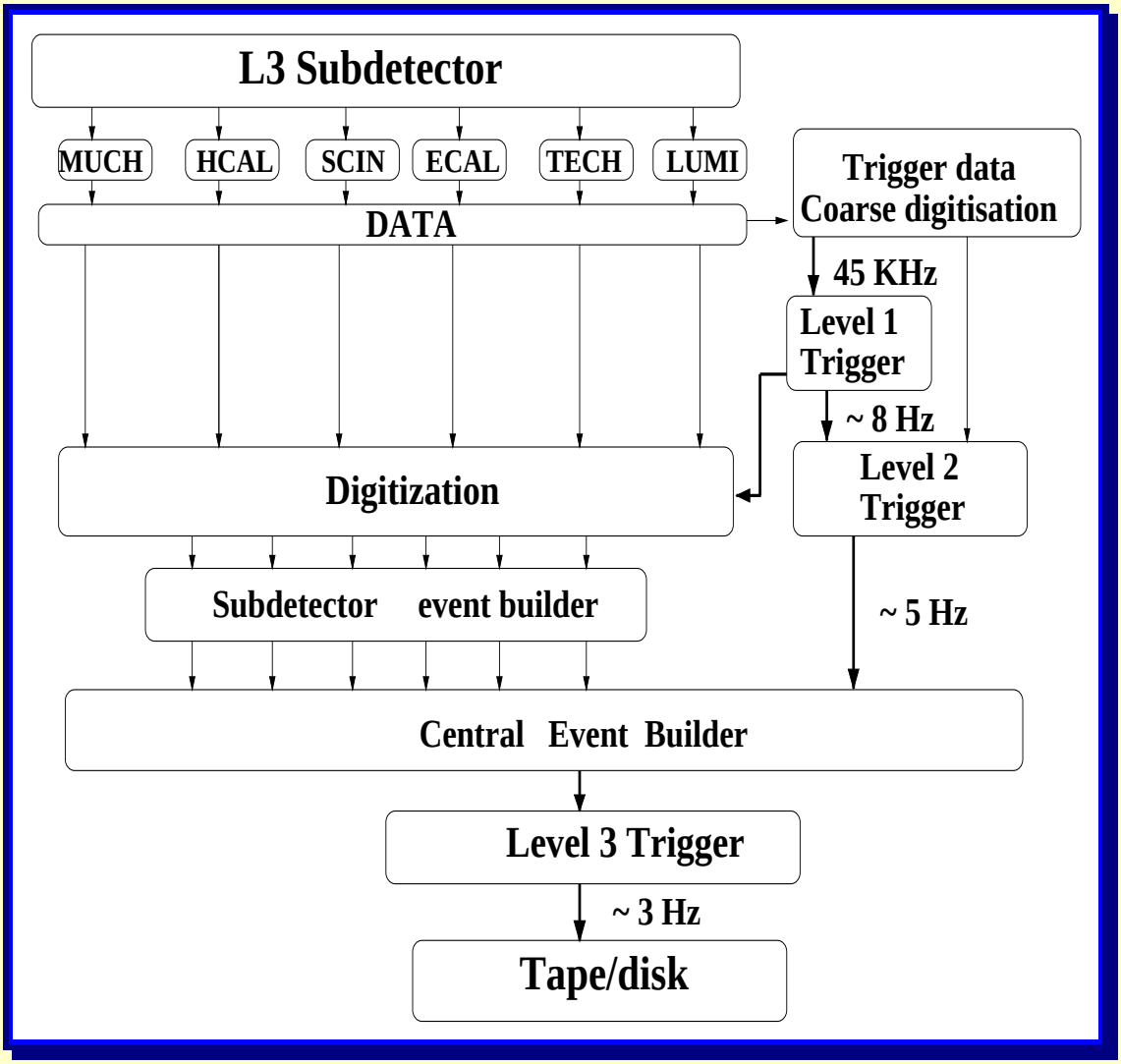
L3 Calorimeters



Luminosity Monitor: 25 mrad $< \theta <$ 70 mrad

L3 Online Trigger System

Beams collide at 45 KHz



Record all interesting physics interactions and reject beam-wall, beam-gas, cosmic rays, etc. background

Hadronic Two-Photon Selection

- $W_{vis} > 3$ GeV
- $E_{total}/\sqrt{s} < 0.38$
- $N_{tracks} \geq 5$
- $E_{Lumi}/E_{Beam} < 0.4$

$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})	Trigger Efficiency	Events	BKG (%)
91	80	0.87	93204	2.4
136	12	0.83	21045	0.2
167	21	0.83	44444	0.2
183	52	0.79	116760	0.2

❒ MC: PYTHIA version 5.722

$e^+e^- \rightarrow e^+e^-q\bar{q}$

LO Calculations with $W_{gen} > 3$ GeV

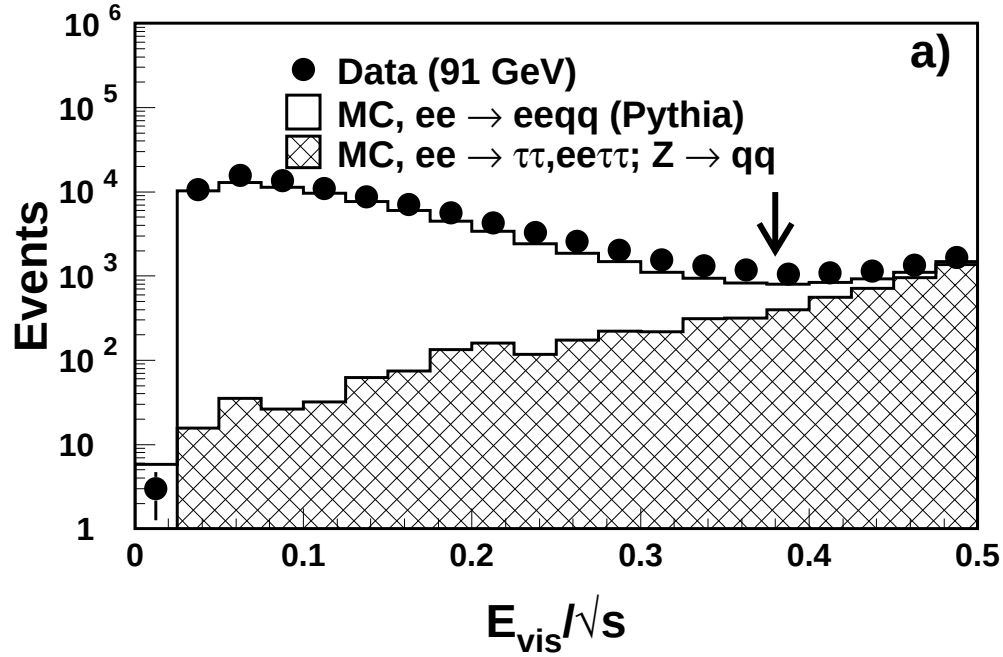
❒ $\mathcal{L}_{\gamma\gamma}$ EPA ($Q^2 < 1$ GeV)

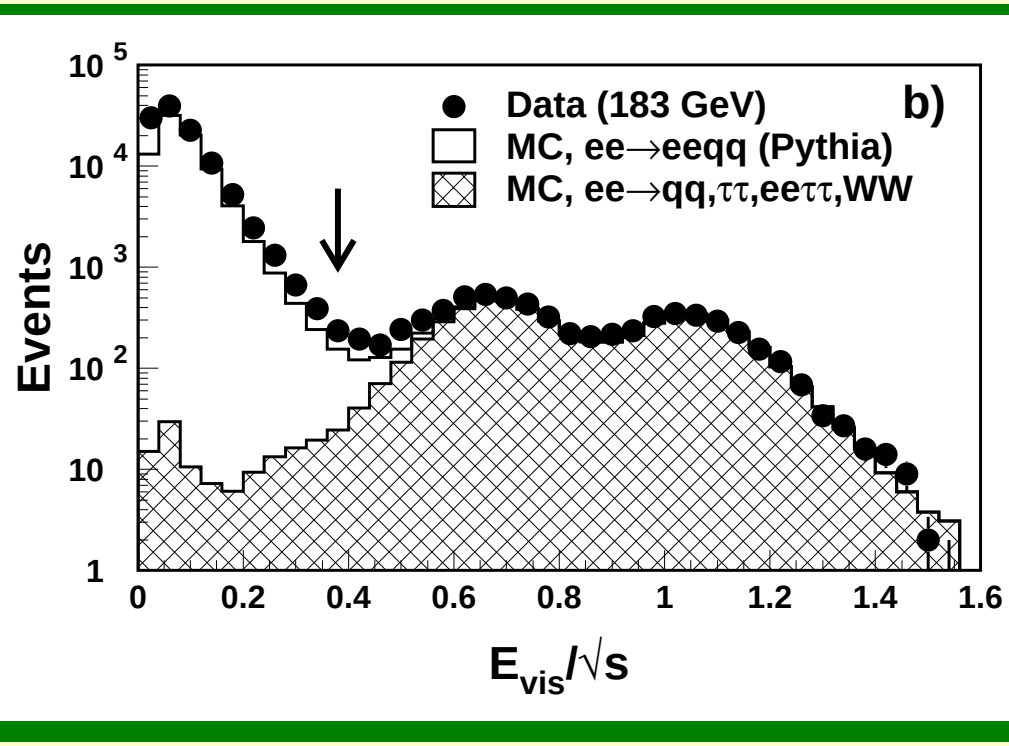
Real Photons

❒ Background Sources

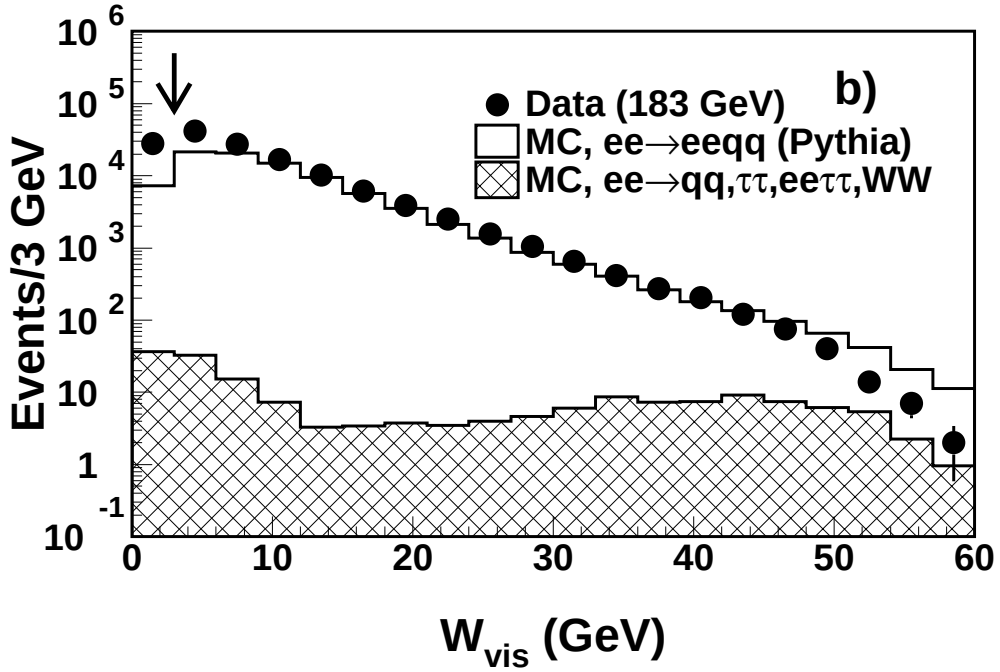
$e^+e^- \rightarrow Z/\gamma \rightarrow q\bar{q}$ (JETSET/PYTHIA)
$e^+e^- \rightarrow \tau^+\tau^-$ (KORALZ)
$e^+e^- \rightarrow W^+W^-$ (KORALW)
$e^+e^- \rightarrow e^+e^-\tau^+\tau^-$ (DIAG36)

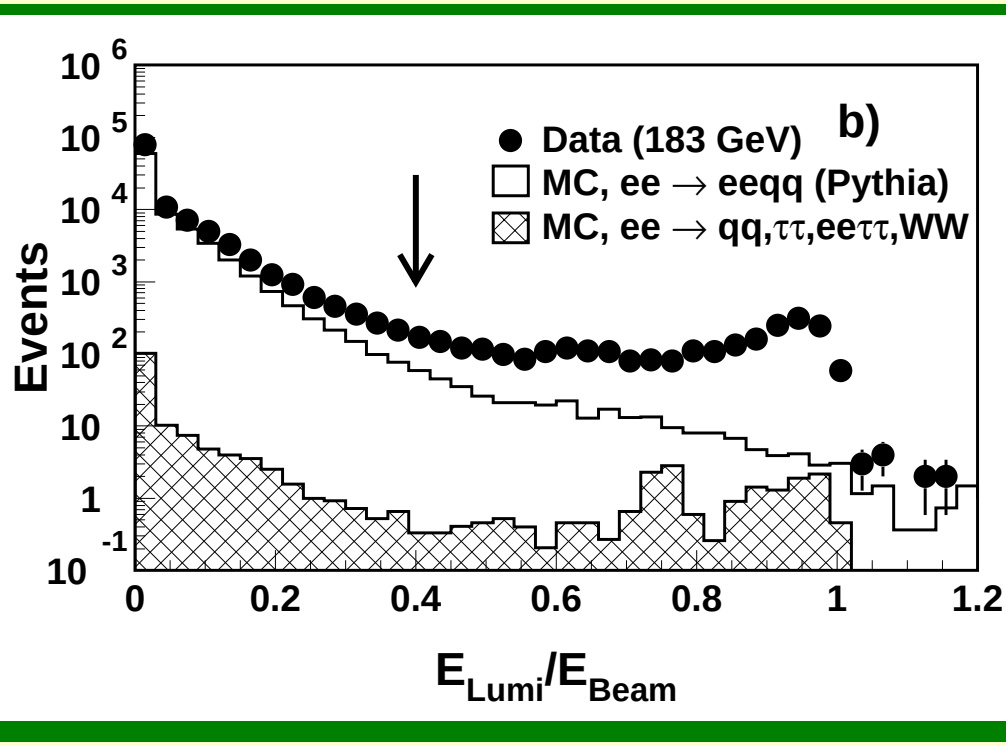
Hadronic Two-Photon Selection



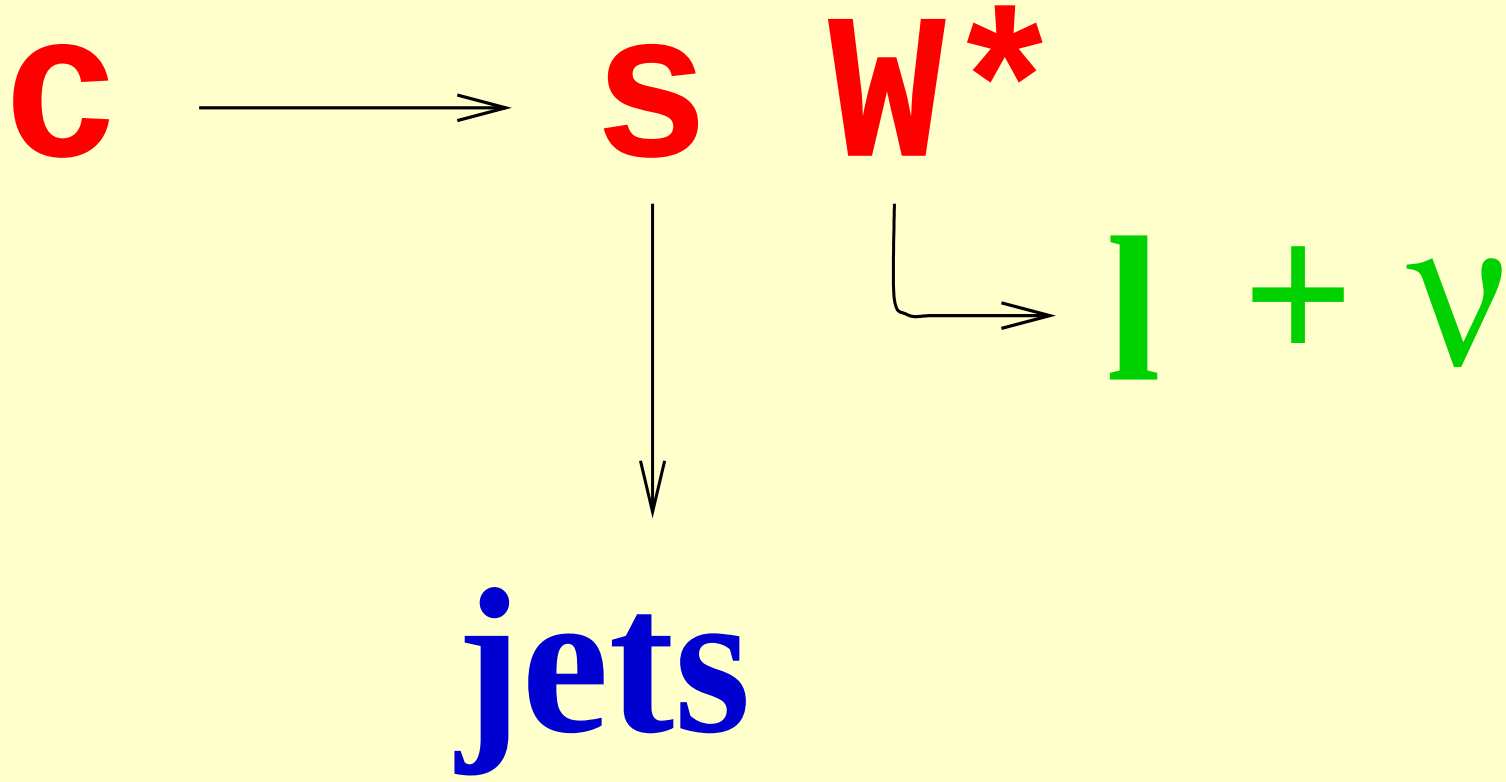


Hadronic Two-Photon Selection

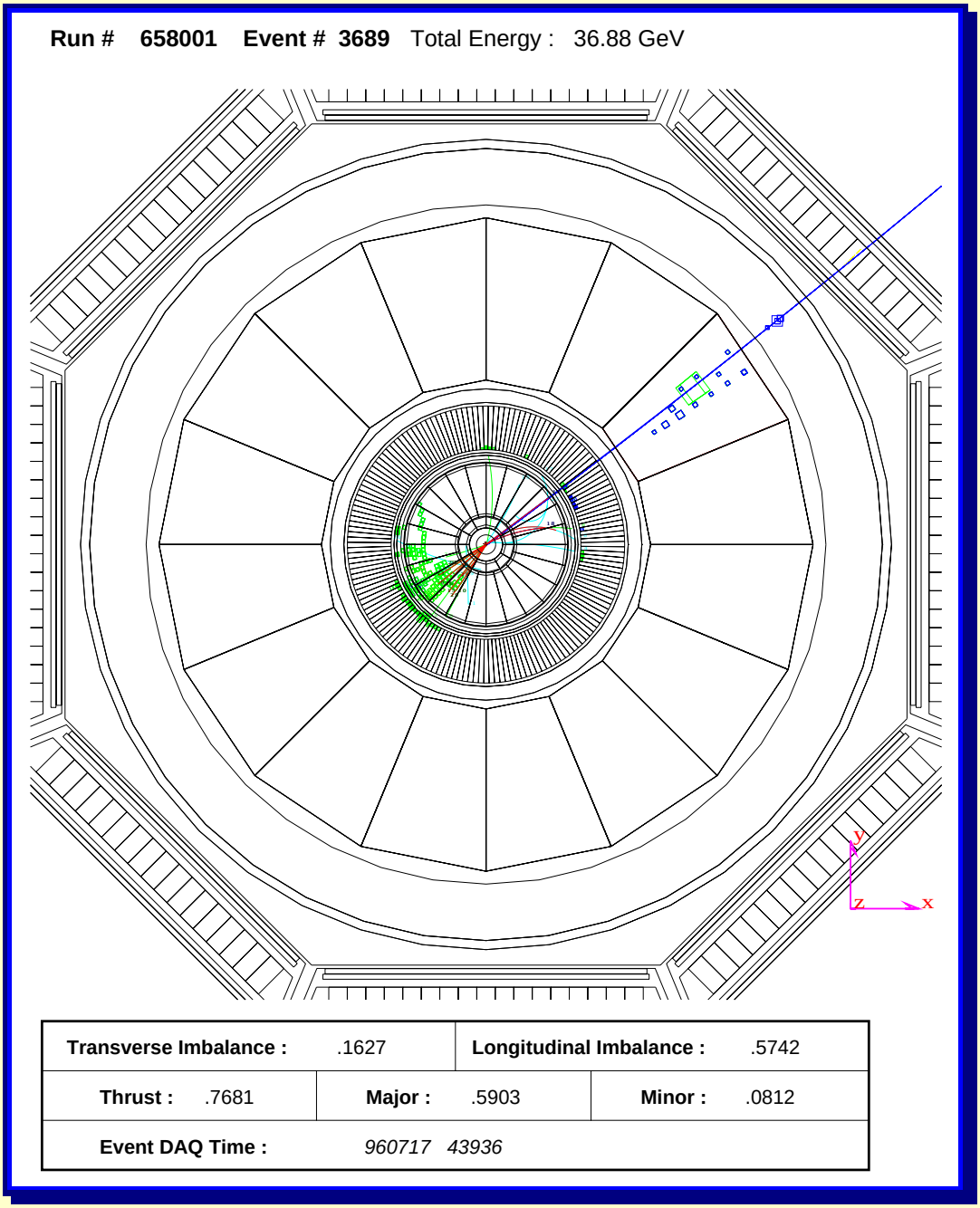




Semi-Leptonic Decay of Charm



Muon Candidate

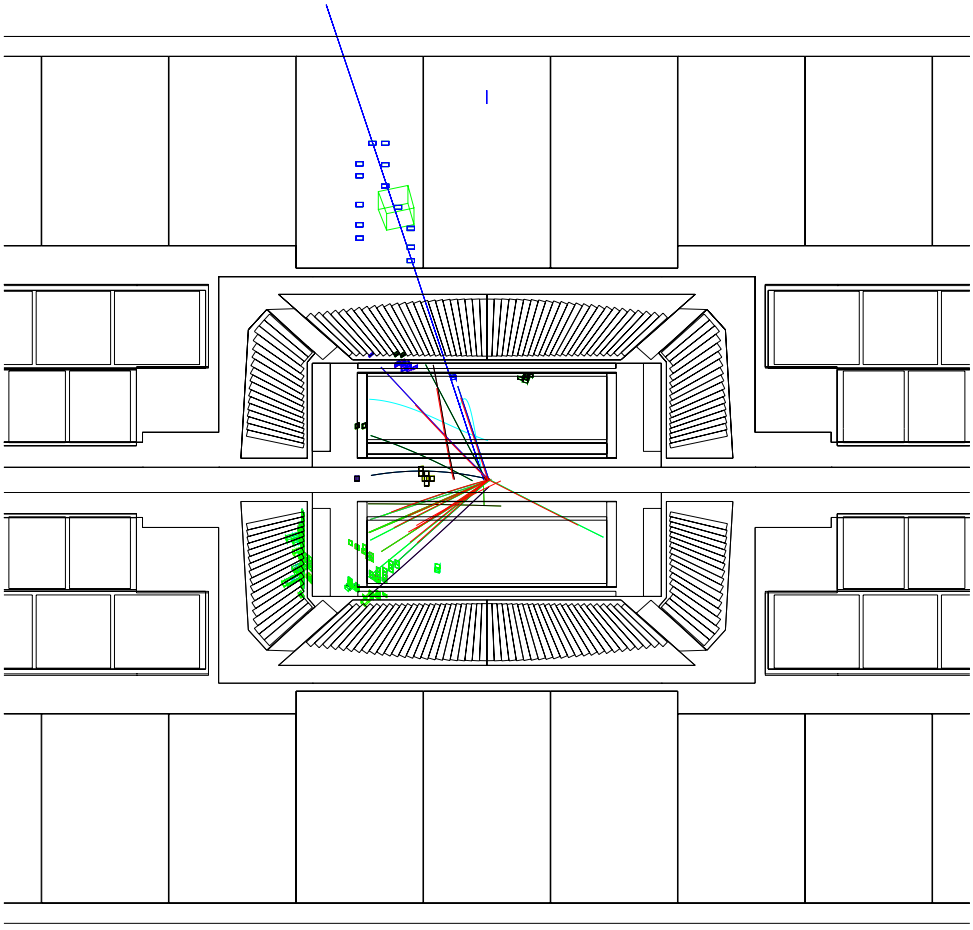


Transverse Imbalance :	.1627		**Longitudinal Imbalance :**	.5742	
Thrust :	.7681	**Major :**	.5903	**Minor :**	.0812
Event DAQ Time :	*960717 43936*				

Transverse view of a two-photon muon-tagged event

Muon Candidate

Run # **658001** **Event #** **3689** Total Energy : 36.88 GeV



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Event DAQ Time :	*960717 43936*				

Longitudinal view of a two-photon muon-tagged event

Lepton Selection

Muon Selection

$|\cos\theta| < 0.90$

$P_\mu > 2$ GeV

$P_\mu < 0.2\ E_{Beam}$

Electron Selection

$|\cos\theta| < 0.90$

$E_e > 0.6$ GeV

$\Delta\phi < 20$ mrad

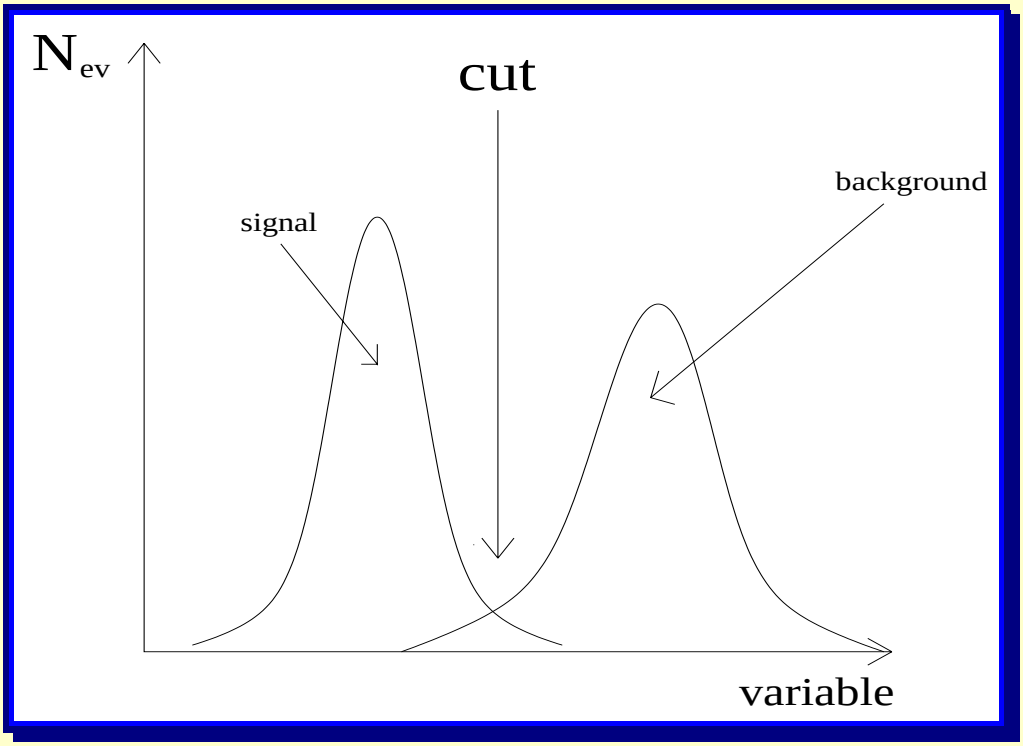
$|DCA| < 0.5$ mm

$\chi^2_{EM} < 3$

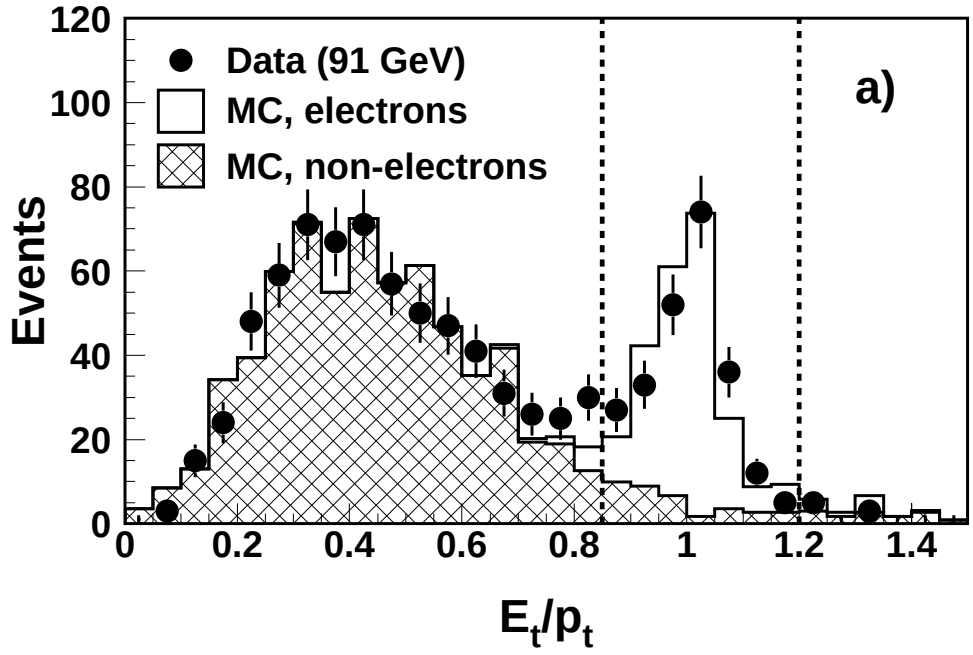
$E_1/E_9 > 0.5$

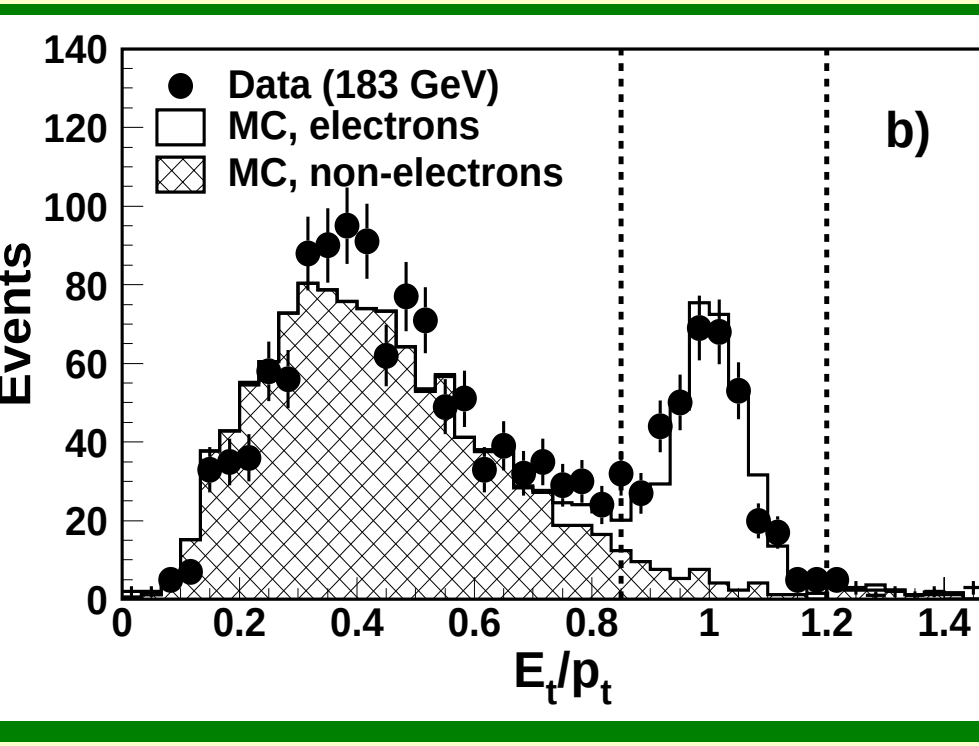
$E_9/E_{25} > 0.95$

$0.85 < E_T/p_T < 1.2$



Electron Selection





Lepton Selection Summary

Electrons

$\sqrt{s}$	N_{OBS}	N_{EXP}	N_{BKG}	N_{conv}	P_e	ϵ_e
91	282	252	29.5	37.1	0.84	0.097
136	82	45	0.5	8.4	0.84	0.084
167	156	112	1.5	22.8	0.85	0.096
183	**433**	**273**	**4.1**	**50.5**	**0.86**	**0.100**

Muons

$\sqrt{s}$	N_{OBS}	N_{EXP}	N_{BKG}	P_μ	ϵ_μ
91	57	45	16.9	1.00	0.33
167	16	15	1.4	1.00	0.33
183	**52**	**39**	**1.4**	**1.00**	**0.33**

- N_{BKG}: **Background from annihilation processes and two-photon production of tau pairs**
- N_{conv}: **Electrons from photon conversions**
- P_e (P_μ): **Electron (Muon) purity**
- ϵ_e (ϵ_μ): **Electron (Muon) selection efficiency**

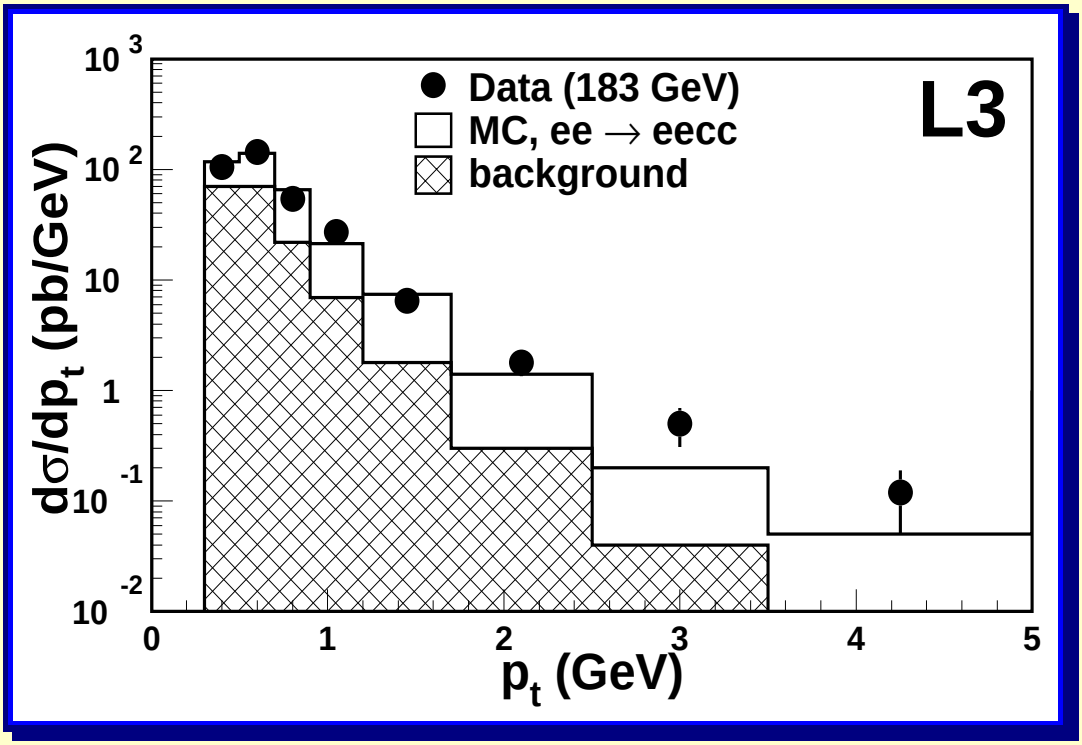
Inclusive Lepton Cross Section

$$e^+e^- \to e^+e^- q\bar{q} \to e^+e^- + \text{hadrons} + \text{lepton}$$

- $W_{\gamma\gamma} > 3$ GeV
- $|\cos\theta| < 0.9$
- $p > 0.6\ (2.0)$ GeV for Electrons (Muons)

$$\Delta\sigma_{\text{lept}} = \frac{[(N^{\text{lept}}_{\text{obs}} - N^{\text{lept}}_{\text{bkg}})\ P_{\text{lept}}] - N_{\text{conv}}}{\mathcal{L}\ \epsilon_{\text{trig}}\ \epsilon_{\text{lept}}}$$

Differential cross section for inclusive electrons as a function of the electron transverse momentum



Excess at high p_t? Beauty?

Inclusive Charm Cross Section

$$e^+e^- \to e^+e^- c\bar{c}X$$

$$\sigma = \frac{(N_{obs}^{lept} - N_{bkg}^{lept})\ \pi_c}{\mathcal{L}\ \epsilon_{trig}\ \epsilon_c'}$$

$$\pi_c = \frac{N_c^{lept}}{N_c^{lept} + N_{nc}^{lept}}$$

..to be less dependent on Monte Carlo flavor composition (charm and non-charm)...

$$\pi_c = (1 - \frac{\epsilon_{nc}}{\epsilon_d})/(1 - \frac{\epsilon_{nc}}{\epsilon_c})$$

$$\epsilon_d = \frac{N_c^{lept} + N_{nc}^{lept}}{N_c^{had} + N_{nc}^{had}} = \frac{N_{obs}^{lept} - N_{bkg}^{lept}}{N_{obs}^{had} - N_{bkg}^{had}}$$

$$\frac{N_c^{lept} + N_{nc}^{lept}}{\epsilon_d} = \frac{N_c^{lept}}{\epsilon_c} + \frac{N_{nc}^{lept}}{\epsilon_{nc}}$$

had : after hadronic two-photon selection
lept: after final selection with lepton tag

Charm Analysis Summary

Electron Tag

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N^e_{obs} Events	N^e_{bkg} Events	π^e_c [%]	$\epsilon^{e\prime}_c$ [10^{-2}%]
91	79.8	282	29.5	50.5 ± 4.9	42.2 ± 3.4
136	12.1	82	0.5	70.0 ± 3.4	42.0 ± 4.0
167	21.2	156	1.5	60.0 ± 3.2	52.6 ± 3.3
183	**52.2**	**433**	**4.1**	$\mathbf{65.9 \pm 2.2}$	$\mathbf{53.3 \pm 2.6}$

Muon Tag

$\sqrt{s}$ [GeV]	$\mathcal{L}$ [pb^{-1}]	N^μ_{obs} Events	N^μ_{bkg} Events	π^μ_c [%]	$\epsilon^{e\prime}_c$ [10^{-2}%]
91	79.8	57	15.9	70.6 ± 8.8	6.43 ± 1.10
167	21.2	16	1.41	48.3 ± 10.1	6.48 ± 1.01
183	**52.2**	**52**	**1.38**	$\mathbf{61.7 \pm 6.8}$	$\mathbf{5.59 \pm 0.83}$

Inclusive Charm Cross Section

❒ $e^+e^- \to e^+e^-c\bar{c}$ (Electron Tag)

$$\sigma_{91\ \mathrm{GeV}} = 435 \pm 64\ (\mathrm{stat}) \pm 76\ (\mathrm{syst})\ [\mathrm{pb}]$$

$$\sigma_{136\ \mathrm{GeV}} = 1358 \pm 243\ (\mathrm{stat}) \pm 180\ (\mathrm{syst})\ [\mathrm{pb}]$$

$$\sigma_{167\ \mathrm{GeV}} = 1009 \pm 152\ (\mathrm{stat}) \pm 106\ (\mathrm{syst})\ [\mathrm{pb}]$$

$$\sigma_{183\ \mathrm{GeV}} = 1291 \pm 105\ (\mathrm{stat}) \pm 122\ (\mathrm{syst})\ [\mathrm{pb}]$$

❒ $e^+e^- \to e^+e^-c\bar{c}$ (Muon Tag)

$$\sigma_{91\ \mathrm{GeV}} = 601 \pm 168\ (\mathrm{stat}) \pm 75\ (\mathrm{syst})\ [\mathrm{pb}]$$

$$\sigma_{167\ \mathrm{GeV}} = 576 \pm 361\ (\mathrm{stat}) \pm 197\ (\mathrm{syst})\ [\mathrm{pb}]$$

$$\sigma_{183\ \mathrm{GeV}} = 1260 \pm 328\ (\mathrm{stat}) \pm 246\ (\mathrm{syst})\ [\mathrm{pb}]$$

Systematic Errors

Electron Tag

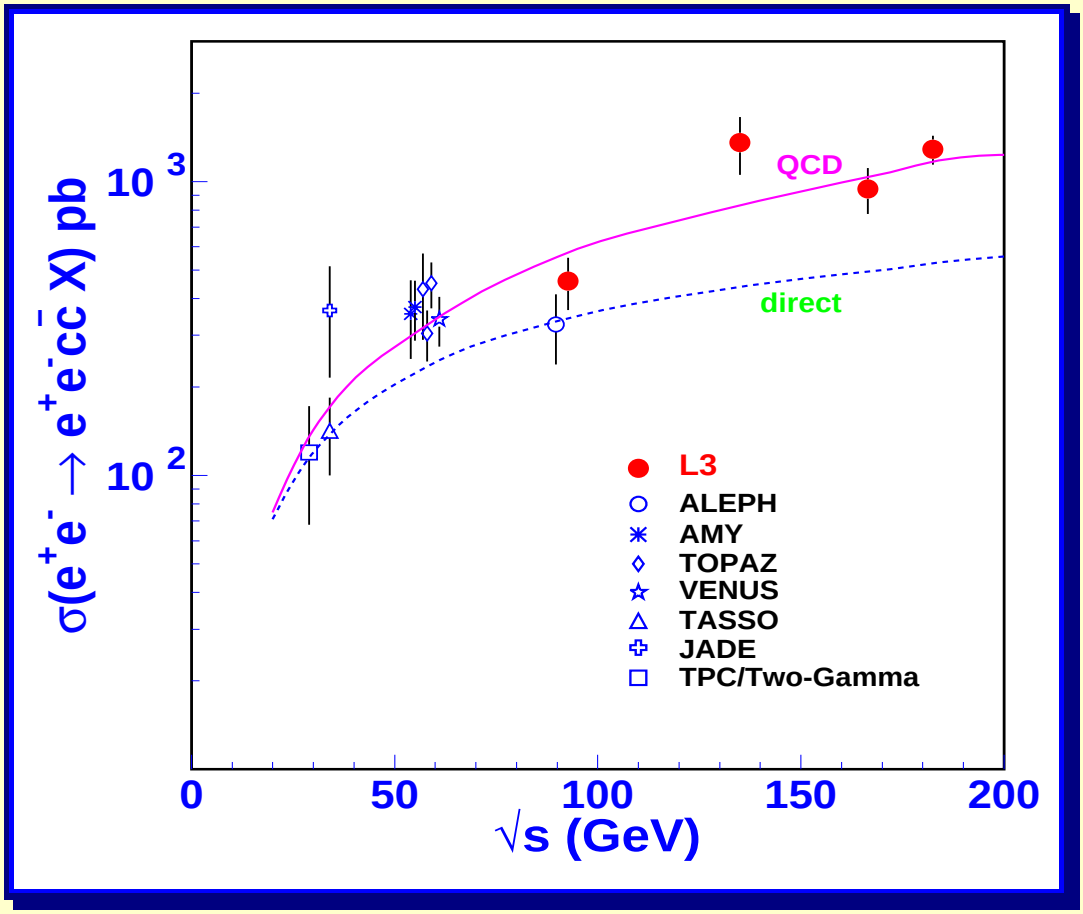
$\sqrt{s}$ [GeV]	91	136	167	183
Charm purity	42.2	66.8	54.5	42.6
Charm selection eff.	35.0	129.3	63.6	63.3
Background	28.7	20.2	15.0	10.3
Trigger efficiency	4.8	40.5	22.2	18.1
Visible mass cut	32.0	100.8	14.0	64.6
Visible energy cut	2.6	0.7	0.1	9.0
E_{Lumi}/E_{Beam} cut	6.5	14.4	2.0	1.0
Momentum cut	0.1	28.0	20.0	25.8
Polar angle cut	8.7	42.0	30.0	19.4
Other electron cuts	37.0	62.7	44.8	43.6
Branching ratio	13.0	40.8	30.3	38.7
TOTAL	**76**	**180**	**106**	**122**

Muon Tag

$\sqrt{s}$ [GeV]	91	167	183
Charm purity	74.5	121.0	139.0
Charm selection eff.	103.0	90.0	186.0
Background	15.0	22.0	13.0
Trigger efficiency	6.6	12.0	18.0
Visible mass cut	12.2	44.0	17.0
Visible energy cut	97.0	51.0	43.0
E_{Lumi}/E_{Beam} cut	0.1	87.0	0.1
Muon cut variation	24.2	11.0	50.1
Branching ratio	18.0	17.3	37.8
TOTAL	**164**	**188**	**246**

Systematic errors quoted in pb

Total Inclusive Charm Cross Section



$e^+e^- \longrightarrow e^+e^- c\bar{c}X$

$\sigma_{91\ \mathrm{GeV}} = 459 \pm 60\ (\mathrm{stat}) \pm 75\ (\mathrm{syst})\ [\mathrm{pb}]$

$\sigma_{136\ \mathrm{GeV}} = 1358 \pm 243\ (\mathrm{stat}) \pm 180\ (\mathrm{syst})\ [\mathrm{pb}]$

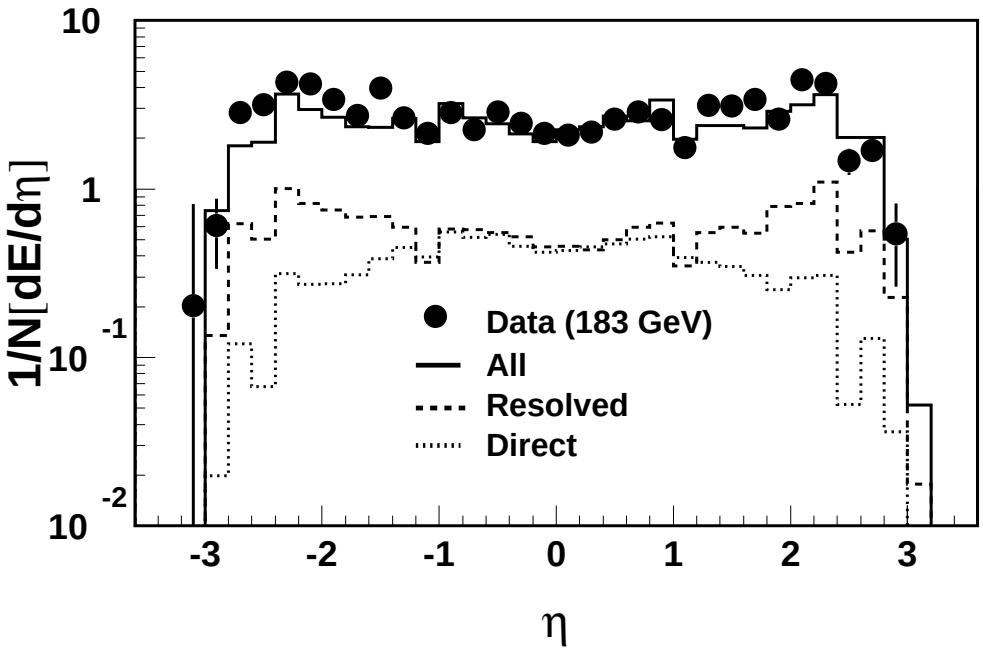
$\sigma_{167\ \mathrm{GeV}} = 936 \pm 140\ (\mathrm{stat}) \pm 100\ (\mathrm{syst})\ [\mathrm{pb}]$

$\sigma_{183\ \mathrm{GeV}} = 1287 \pm 100\ (\mathrm{stat}) \pm 114\ (\mathrm{syst})\ [\mathrm{pb}]$

Prediction is calculated using $m_c = 1.3\ \mathrm{GeV}$
Renormalization scale chosen to be the charm mass

Direct & Resolved Contributions

Energy flow as function of pseudorapidity



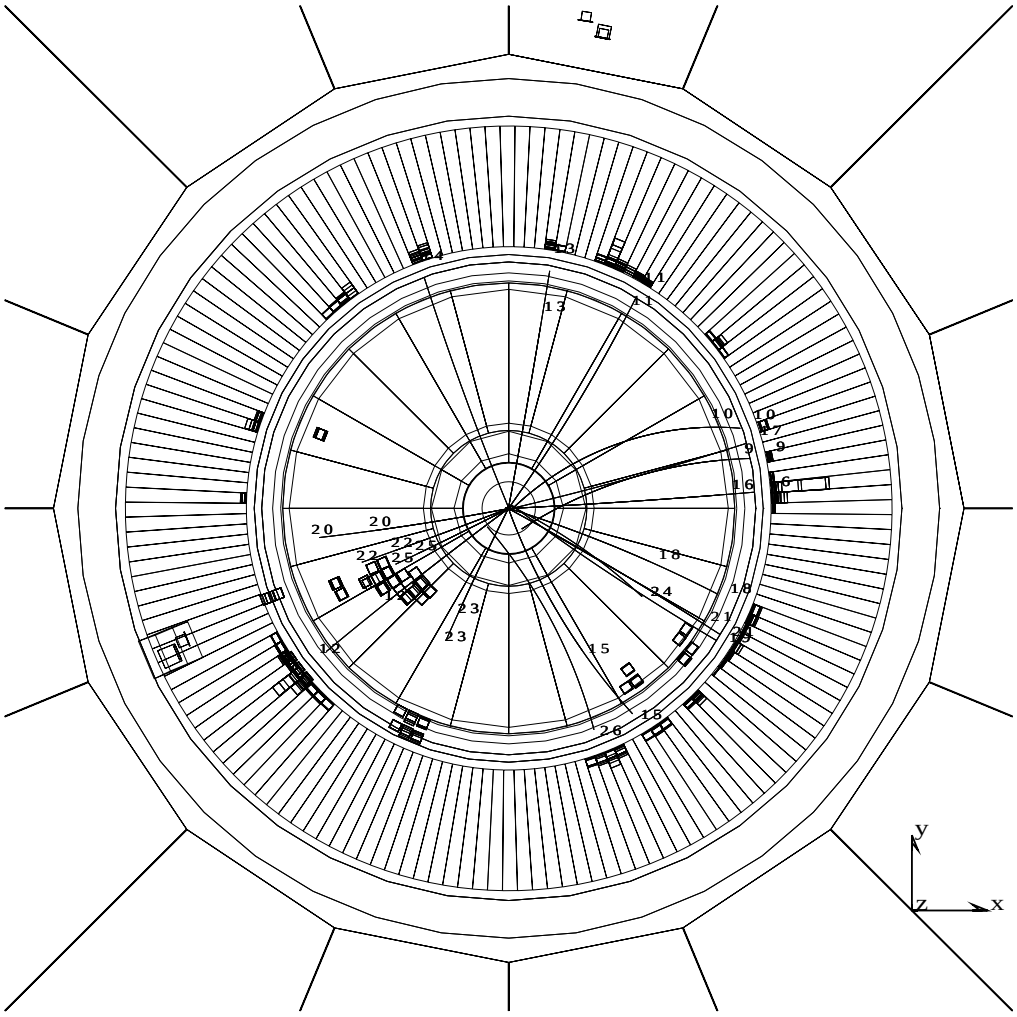
$$\eta = -\ln[\tan(\frac{\theta}{2})]$$

- $\eta = 1.0 \Longrightarrow \theta \simeq 40^\circ$
- $\eta = 1.5 \Longrightarrow \theta \simeq 25^\circ$
- $\eta = 2.0 \Longrightarrow \theta \simeq 15^\circ$

Resolved process has a small angle remnant jet

Electron Candidate

Run # 688501 Event # 1069 Total Energy : 29.94 GeV



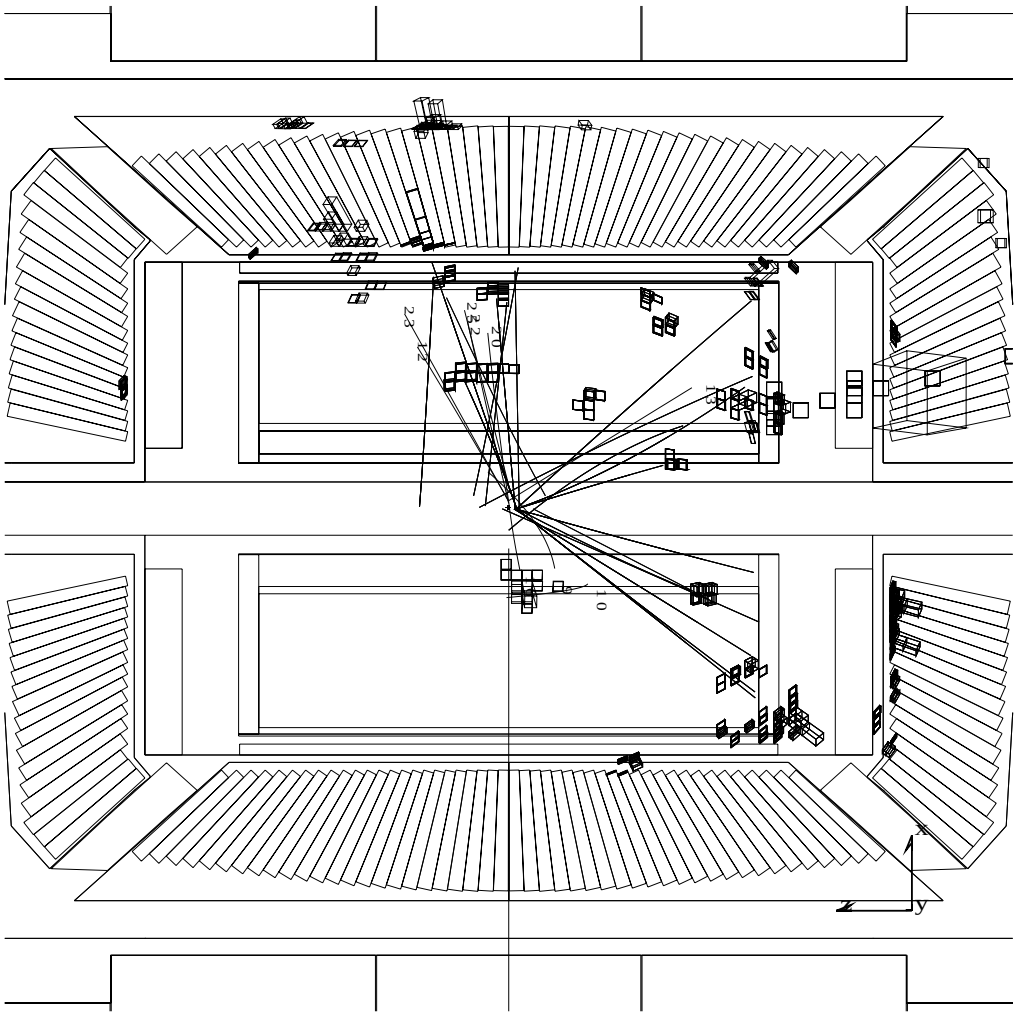
Transverse Imbalance :	.0453		**Longitudinal Imbalance :**	-.5303	
Thrust :	.7080	**Major :**	.4463	**Minor :**	.3052
Event DAQ Time :	*971027 145523*				

Transverse view of a two-photon electron-tagged event

p = 2.3 GeV and $\phi = 3^\circ$

Electron Candidate

Run # 688501 Event # 1069 Total Energy : 29.94 GeV



Transverse Imbalance :	.0453		**Longitudinal Imbalance :**	-.5303	
Thrust :	.7080	**Major :**	.4463	**Minor :**	.3052
Event DAQ Time :	*971027 145523*				

Longitudinal view of a two-photon electron-tagged event

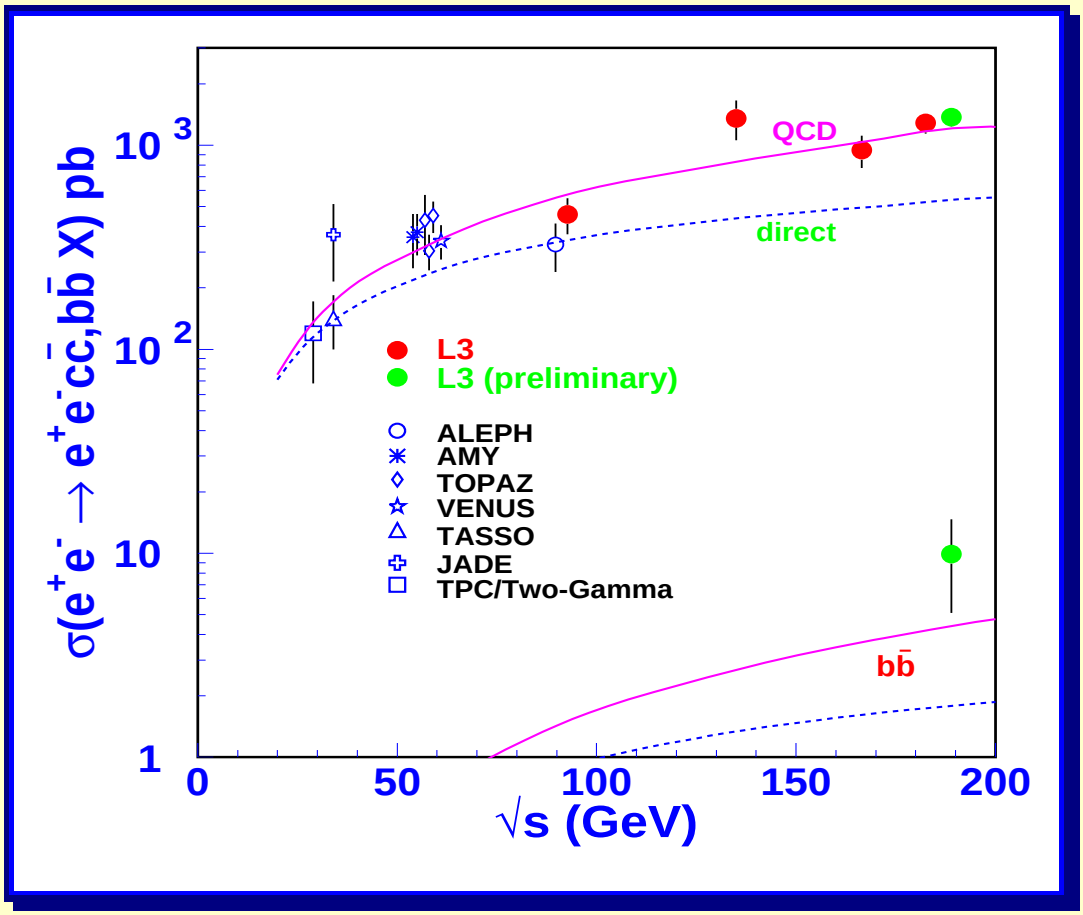
3 jets: Resolved remant or Gluon Radiation

p = 2.3 GeV and $\phi = 73°$

Summary

- Measured $\sigma(e^+e^- \to e^+e^- c\bar{c}X)$ in the center-of-mass range of $91\ \mathrm{GeV} \leq \sqrt{s} \leq 183\ \mathrm{GeV}$
- Cross section $\Uparrow$ with $\sqrt{s}$ as expected by QCD prediction
- Observed data exceed PYTHIA prediction (leading order calculations) by 60% at 183 GeV. NLO corrections need to be included in the next generation of Monte Carlos
- Direct process, even with real and virtual gluon corrections, is insufficient to describe the data. Need resolved processes
  $\Longrightarrow$ Data require a significant gluon content in the photon
- Direct contribution to cross section dependent on the charm mass. Model total cross section as the sum of direct and resolved components $\Longrightarrow$ Perform fit to determine relative amounts
- Higher luminosity and $\sqrt{s}$, improve statistical uncertainty on charm cross section. Also, beauty production can be measured for first time in $\gamma\gamma$ collisions

Preliminary Results



$e^+e^- \to e^+e^- c\bar{c}X$

$N_{electrons} = 1710 \quad N_{muons} = 208$

$\sigma_{189\ GeV} = 1378 \pm 55$ (stat) ± 134 (syst) [pb]

$e^+e^- \to e^+e^- b\bar{b}X$

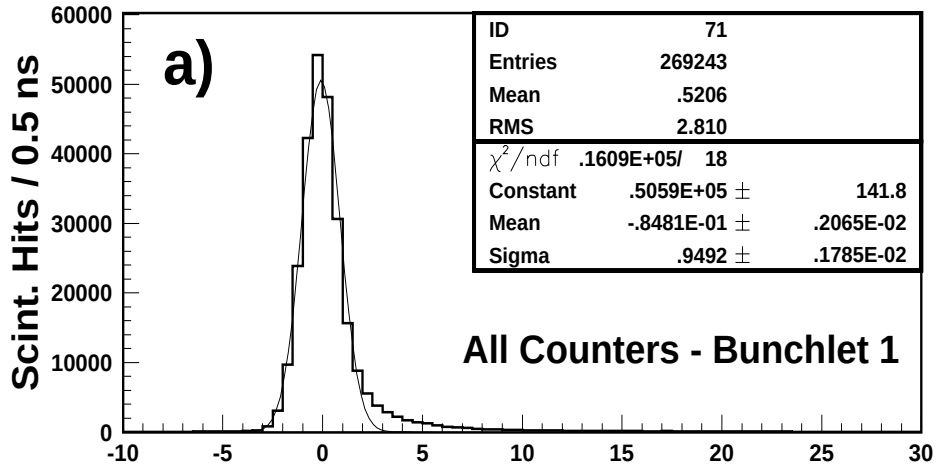
$N_{electrons} = 96 \quad N_{muons} = 49$

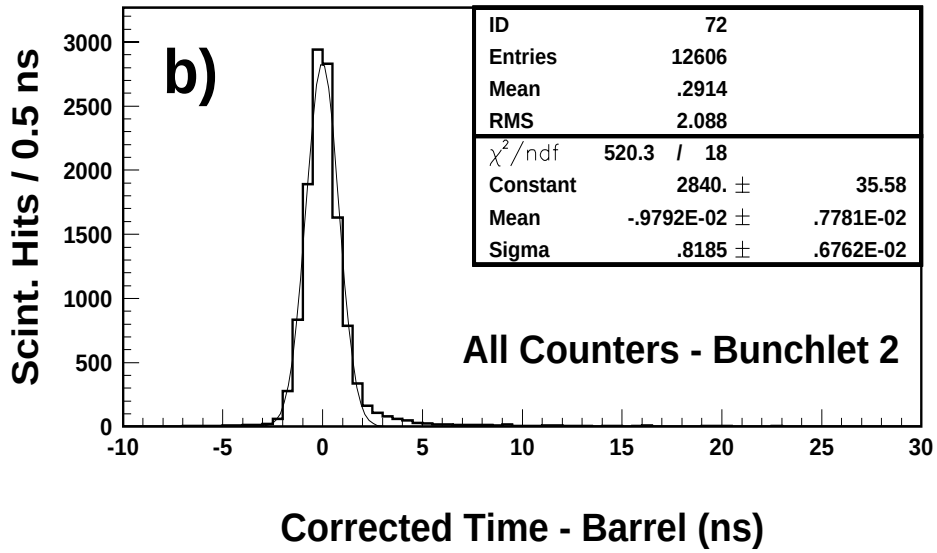
$\sigma_{189\ GeV} = 9.9 \pm 2.9$ (stat) ± 3.8 (syst) [pb]

Scintillators

1998 Data Period

Average corrected time resolution for the 30 barrel scintillators

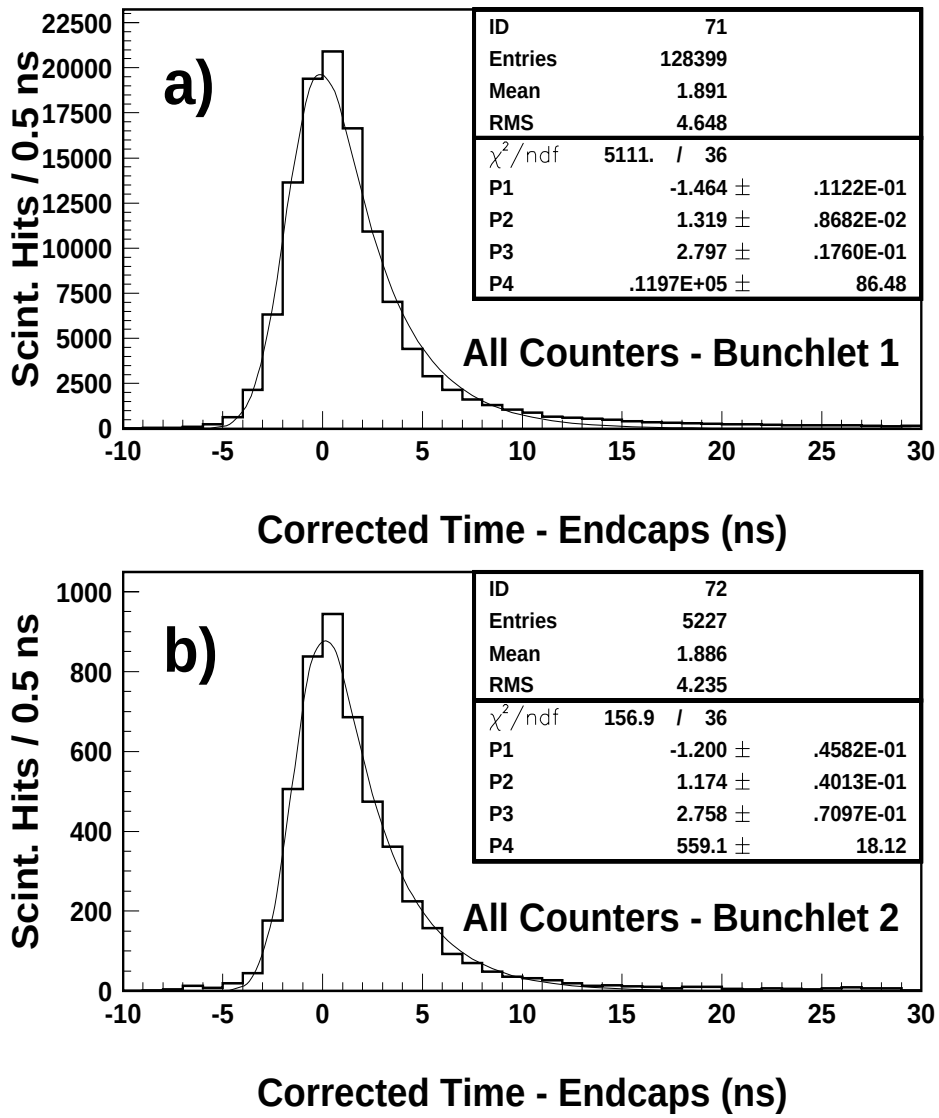




Scintillators

1998 Data Period

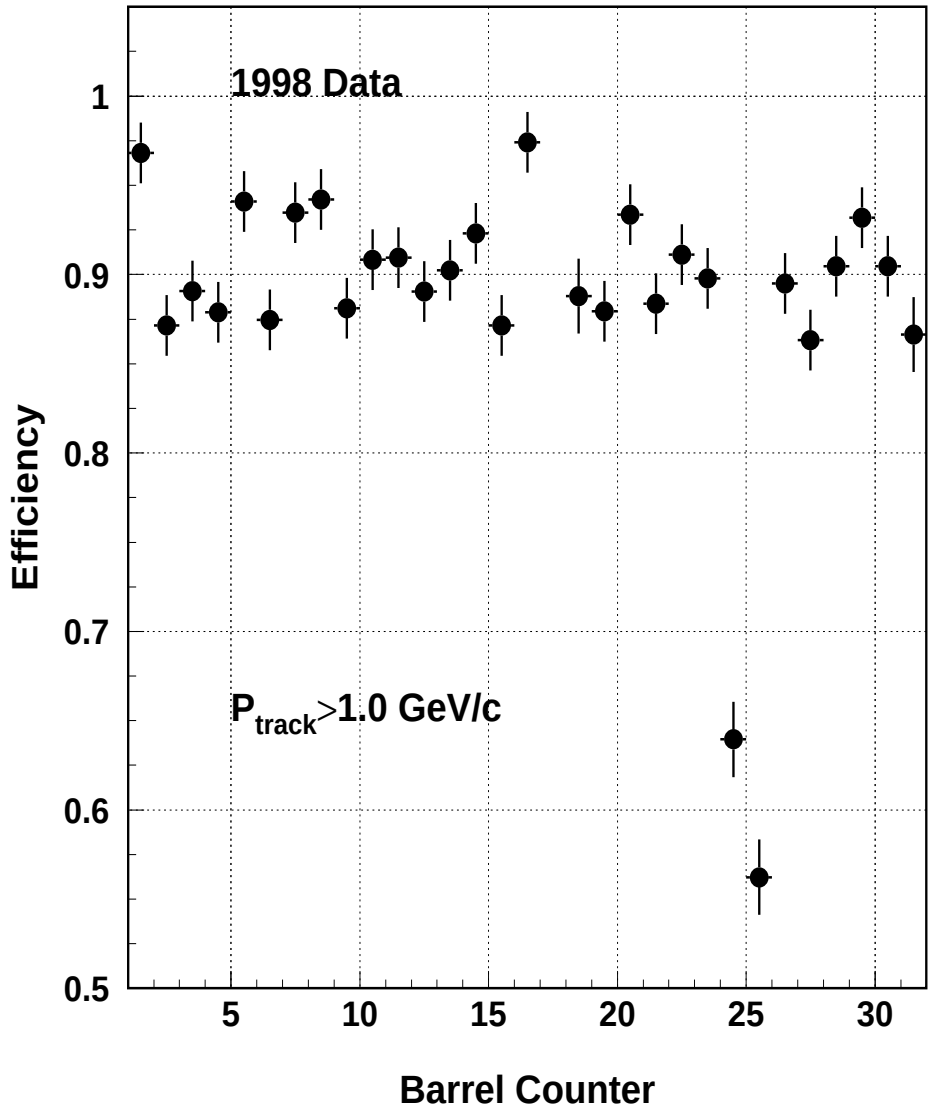
Average corrected time resolution for the 32 endcap scintillators



Scintillators

1998 Data Period

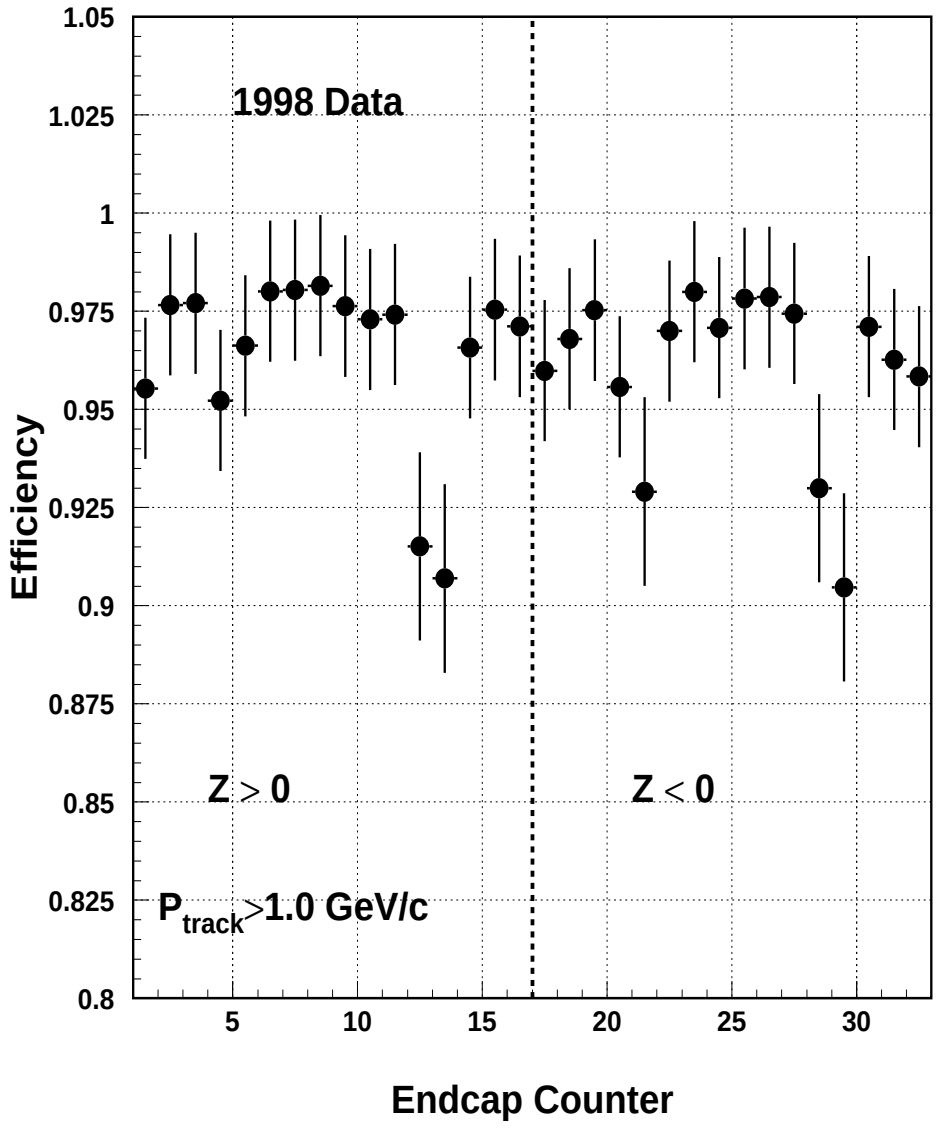
Barrel counter efficiency



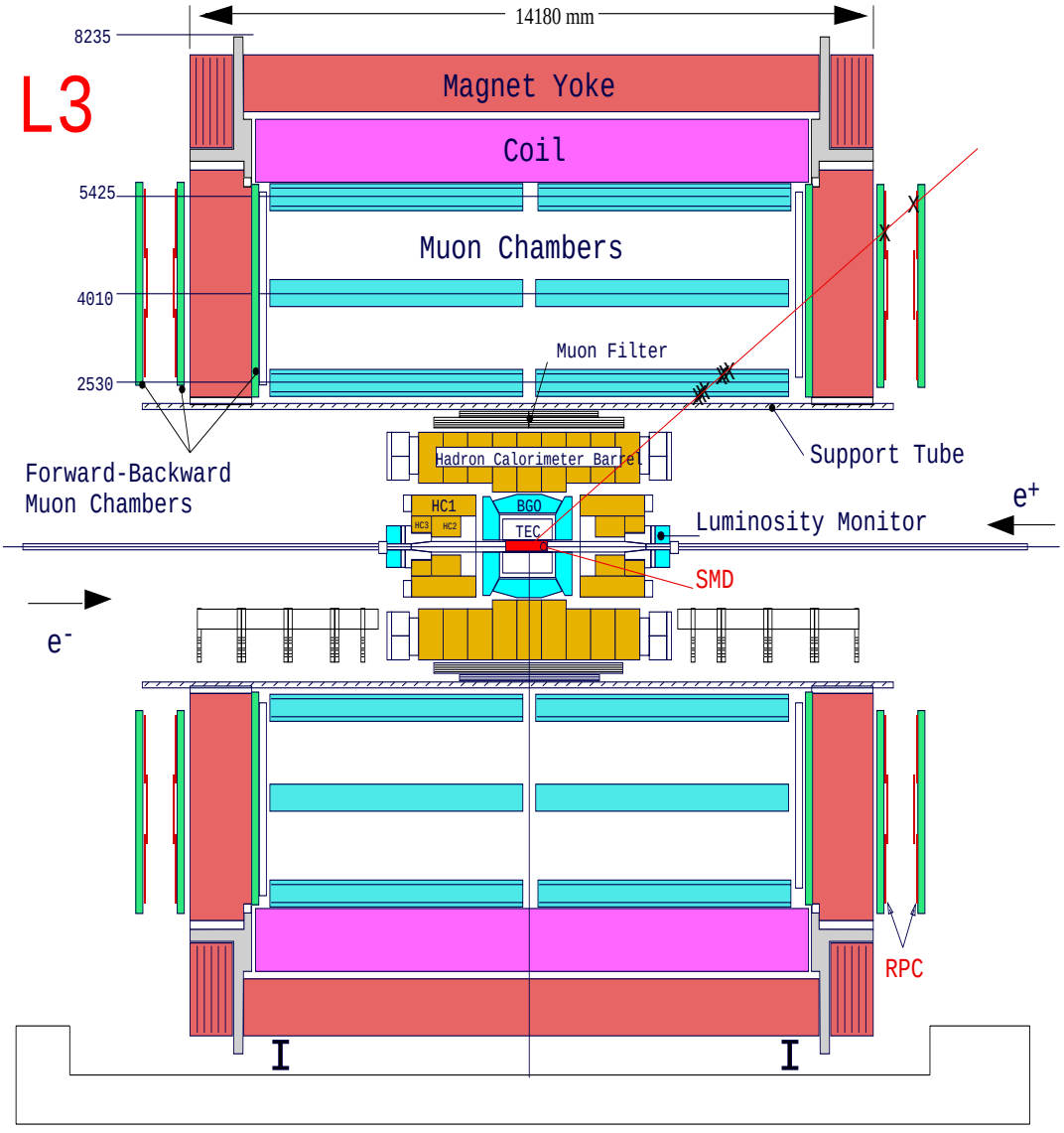
Scintillators

1998 Data Period

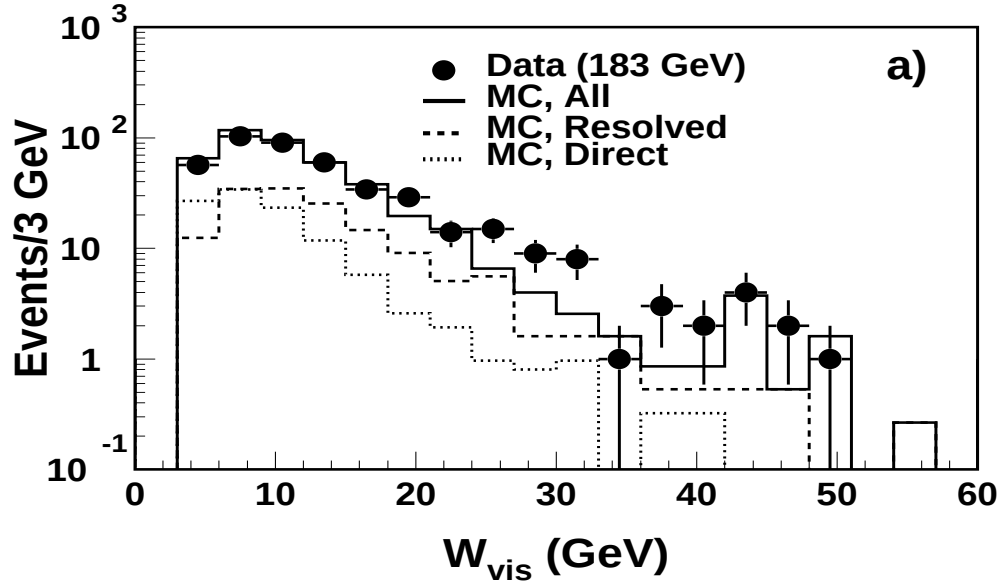
Endcap counter efficiency

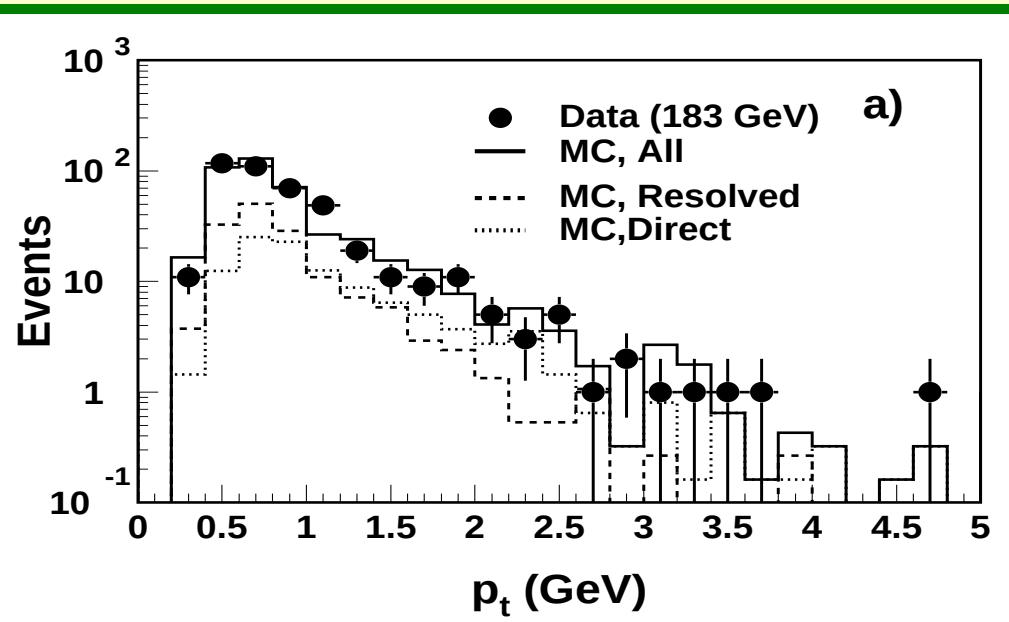


The L3 Detector



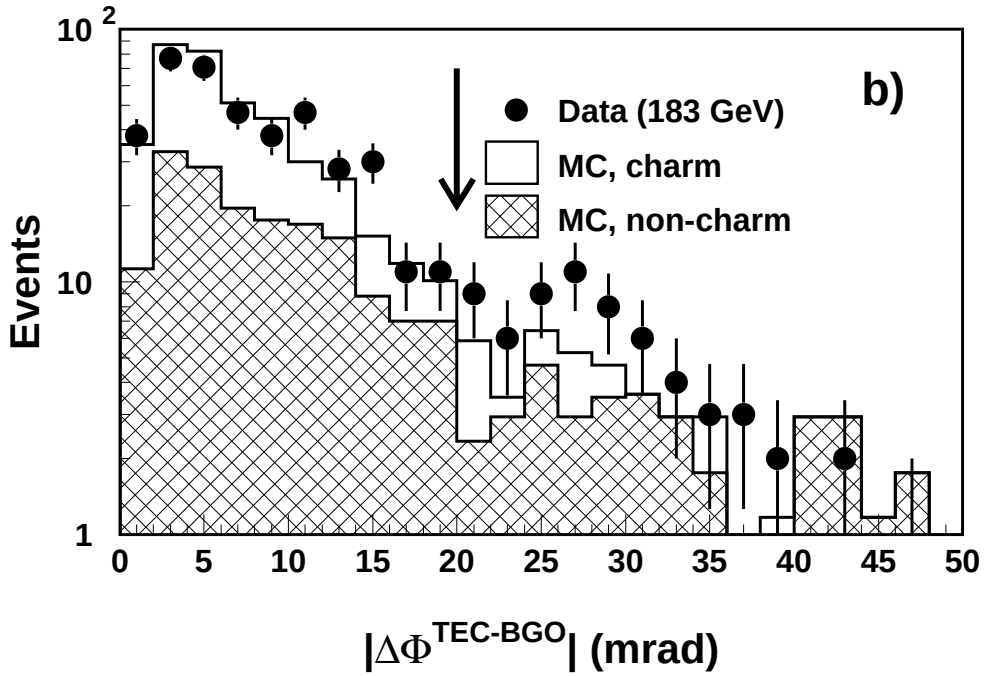
Direct & Resolved Process

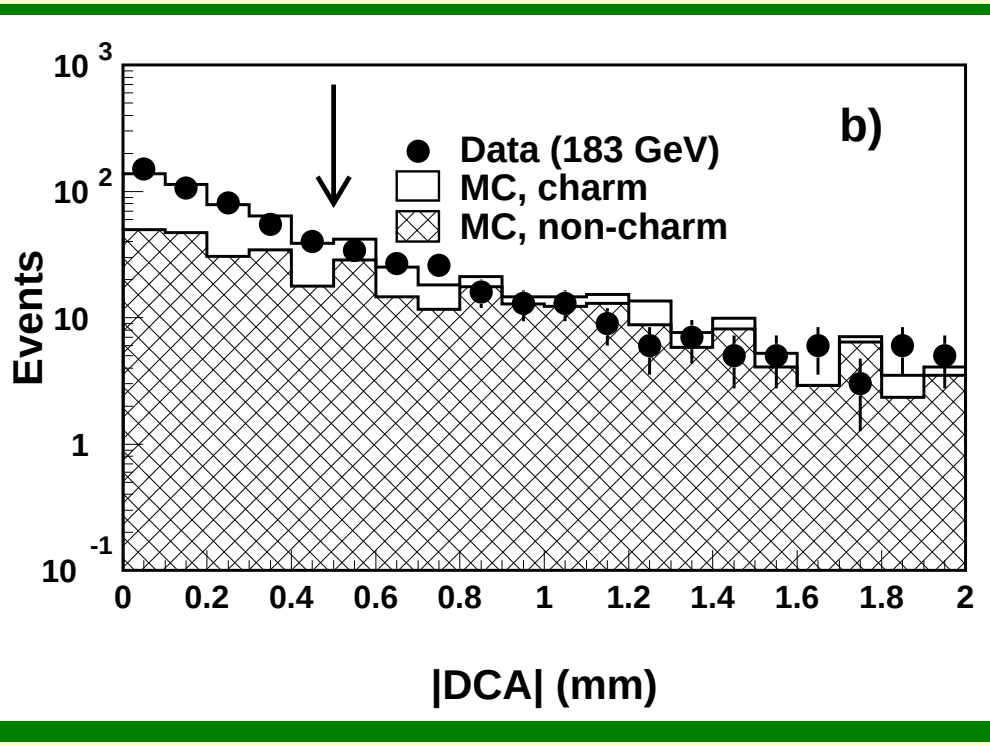




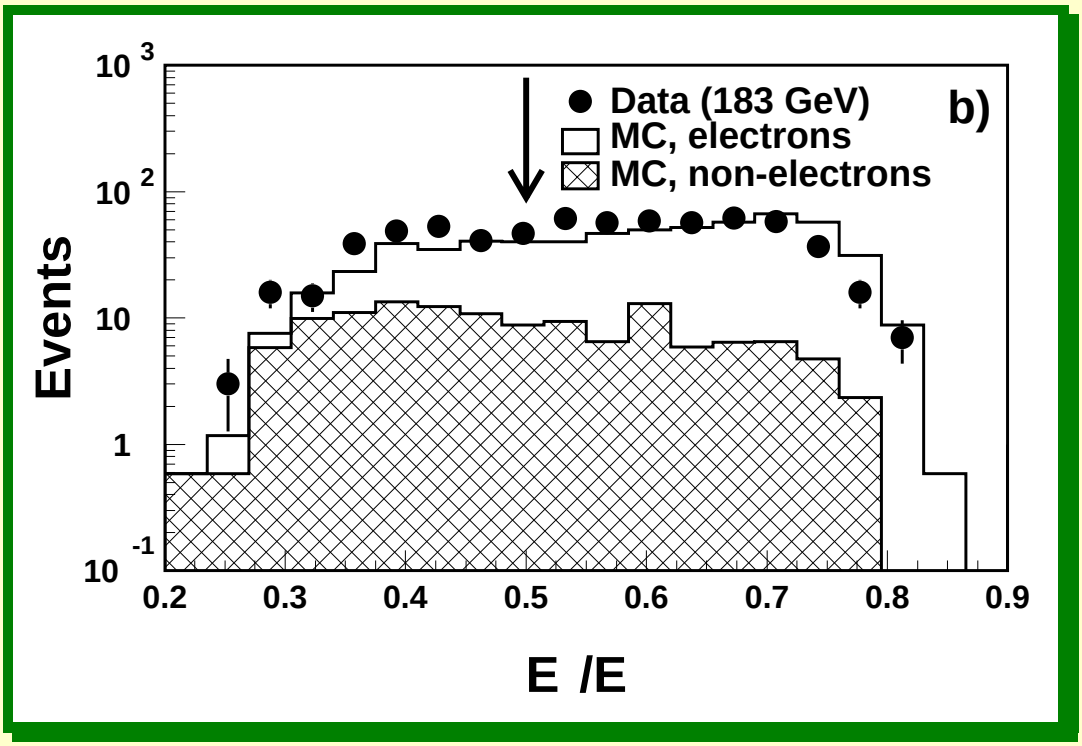
Resolved events require more visible mass to produce charm pair because of the remnant jet

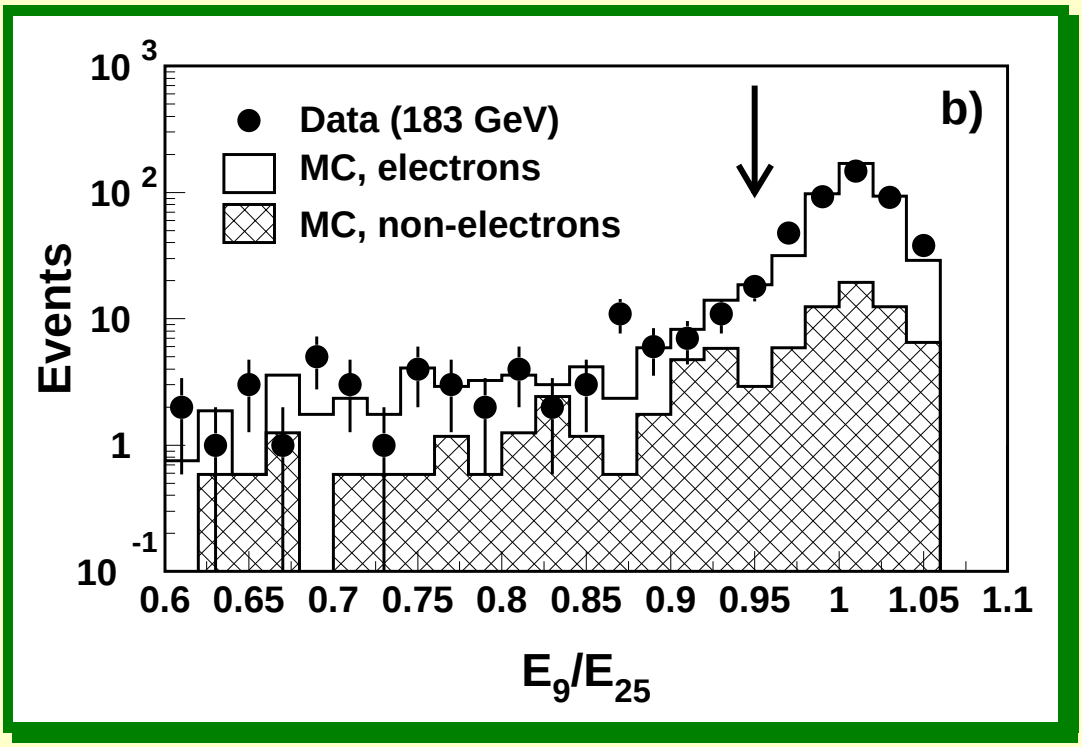
Electron Selection



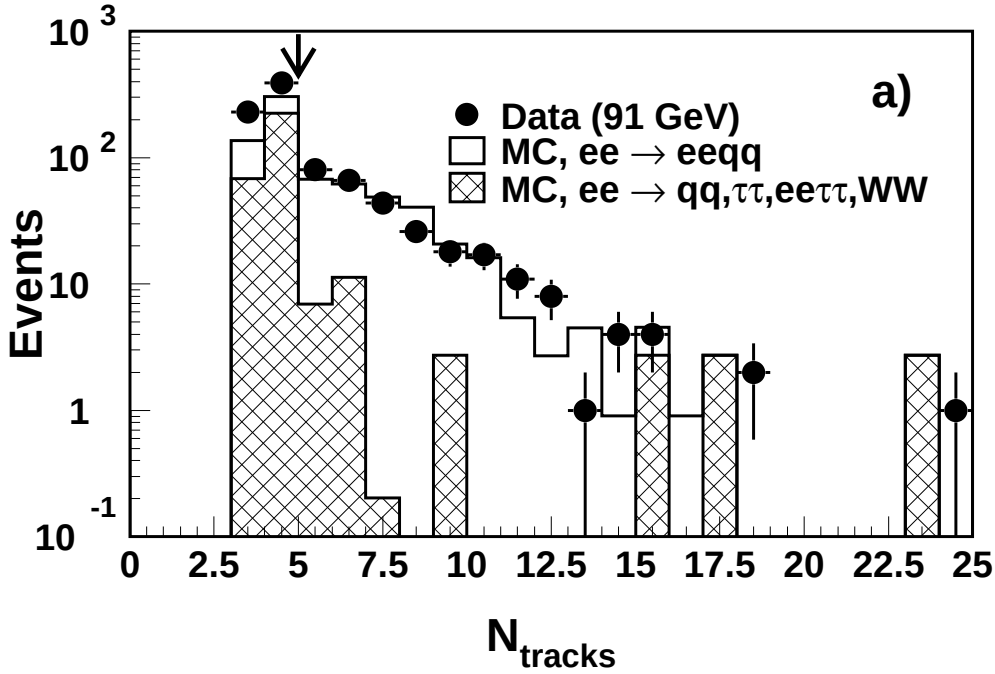


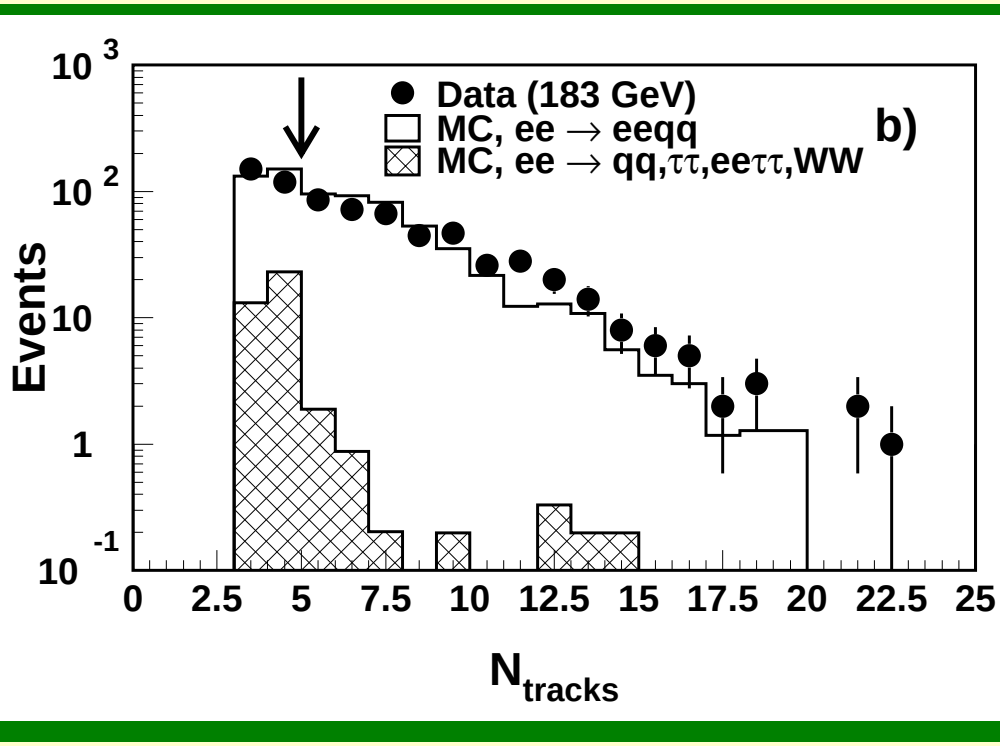
Electron Selection



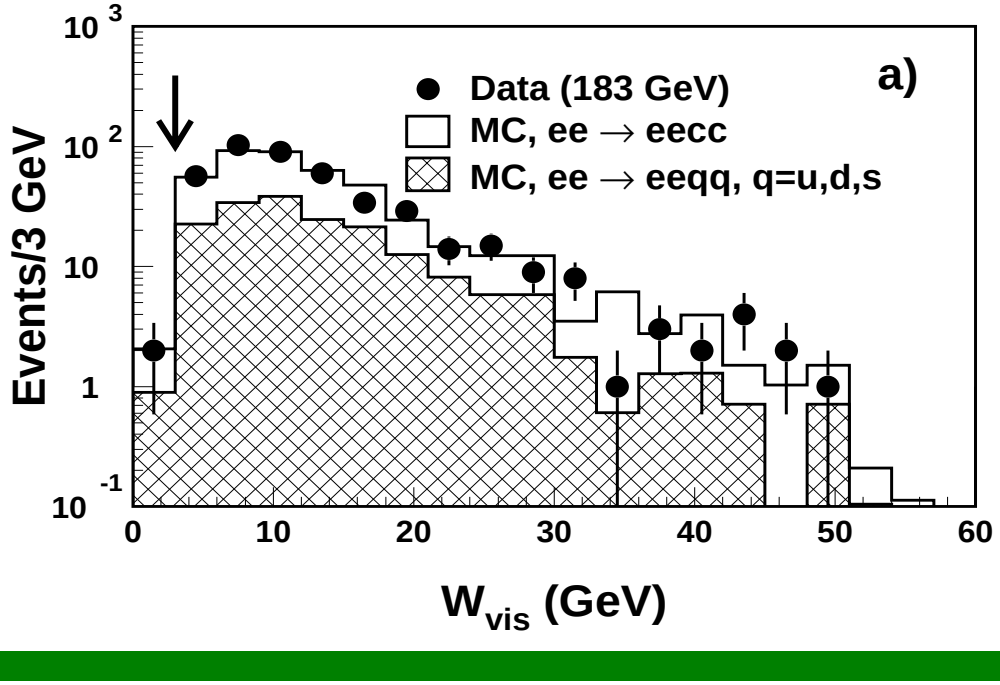


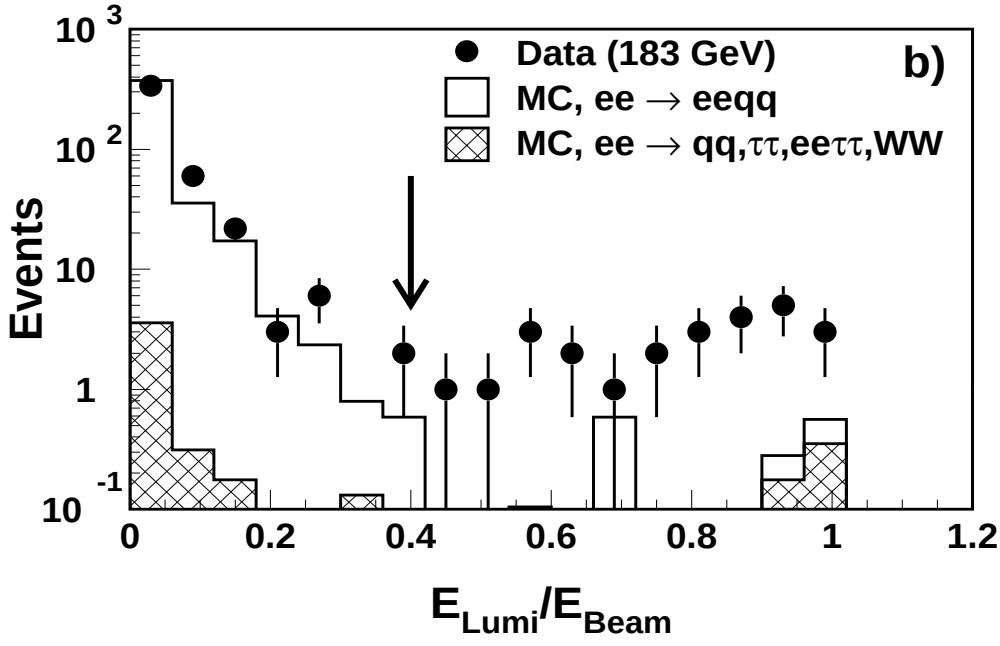
Final Event Distributions





Final Event Distributions





- No signal charm events rejected by W_{vis} cut
- Data exceeds MC by 5.5% before anti-tag cut

Muon Selection